SOFTWARE AND SUSTAINABILITY
S2 RESEARCH GROUP

Design and Development of Green Software

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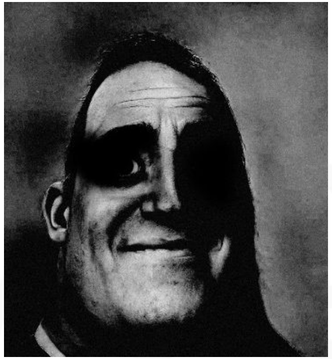
Introduction

Growth of ICT devices and services

Impact on People's Lives | **Energy Demand**



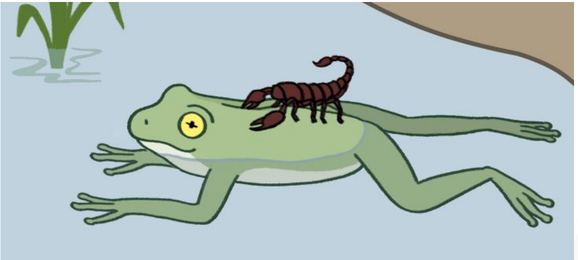
Belkhir et al. estimate that ICT devices will produce **14%** of global CO2 emissions by 2040.

IMG: https://anacurbelol.com/PG-Illustrations

Belkhir, L., Elmeligi, A., Assessing ICT global emissions footprint: Trends to 2040 & recommendations, Journal of Cleaner Production, 2018

Introduction

Current efforts to make ICT more sustainable **are not keeping pace** with the *industry's expansion*



Hardware Power Consumption **savings** *(Frog)*

Poor design decisions at the SW level *(Scorpion)*

Rebound Effect > Data centres and data transmission networks are responsible for 1% of energy-related GHG emissions **(IEA)**

Techniques to reduce **SW energy consumption** are crucial to achieve *Net Zero Goals around 2050*

IMG: https://anacurbelol.com/PG-Illustrations

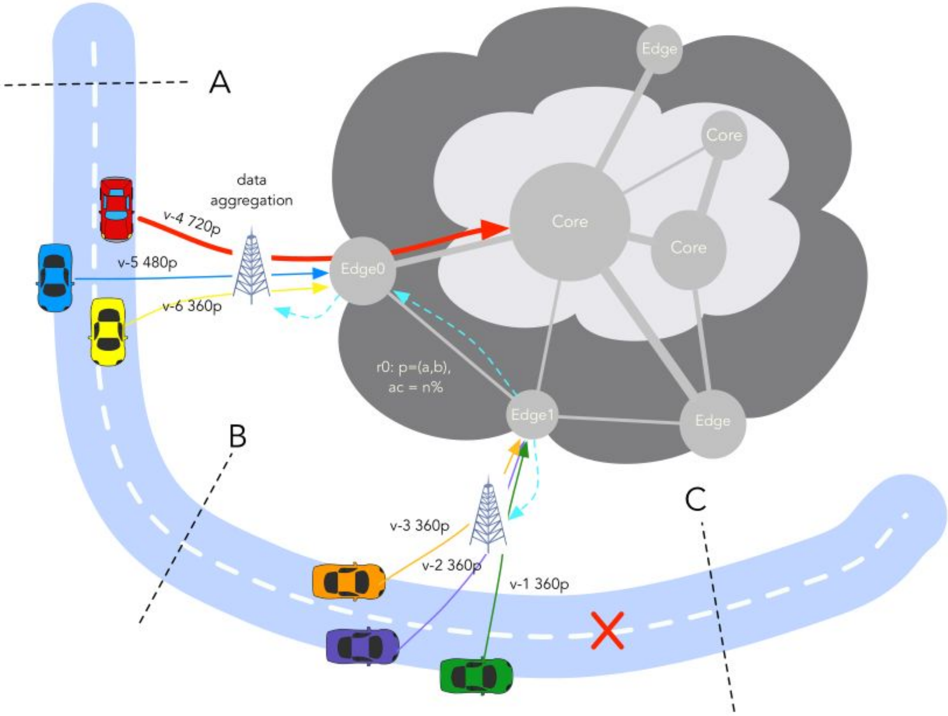
Freitag et al. - *"The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations."* Patterns 2, 2021

IEA, Tracking Clean Energy Progress 2023, https://www.iea.org/reports/tracking-clean-energy-progress-2023

An holistic view of software energy consumption

- **Optimizing** overall energy consumption is **complex**
- SoA offers **domain-specific energy models/techniques**, <u>none of them provides the overall picture</u>
- Identify **energy hotspots**
- Exploit **Modeling** and **Simulation**

Inductive approach: we collect empirical evidence that we analyze



Y. Li et al., "End-to-end energy models for Edge Cloud-based IoT platforms: Application to data stream analysis in IoT" . Future Generation Computer Systems, vol. 87, pp. 667–678, Oct. 2018, doi: 10.1016/j.future.2017.12.048.

Green Architectural Tactics for the Cloud

tactics: "***design decisions*** that influence the achievement of **a quality attribute response**"

Example: Apply Edge Computing

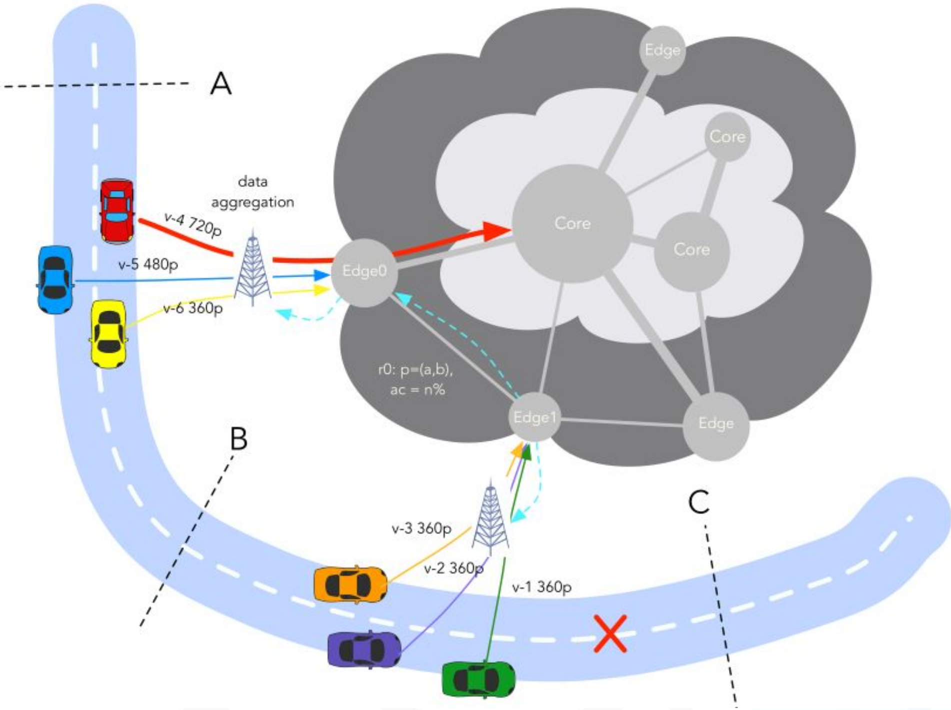
Real-Time Object Detection

QoS depends on connectivity

Edge Benefits:

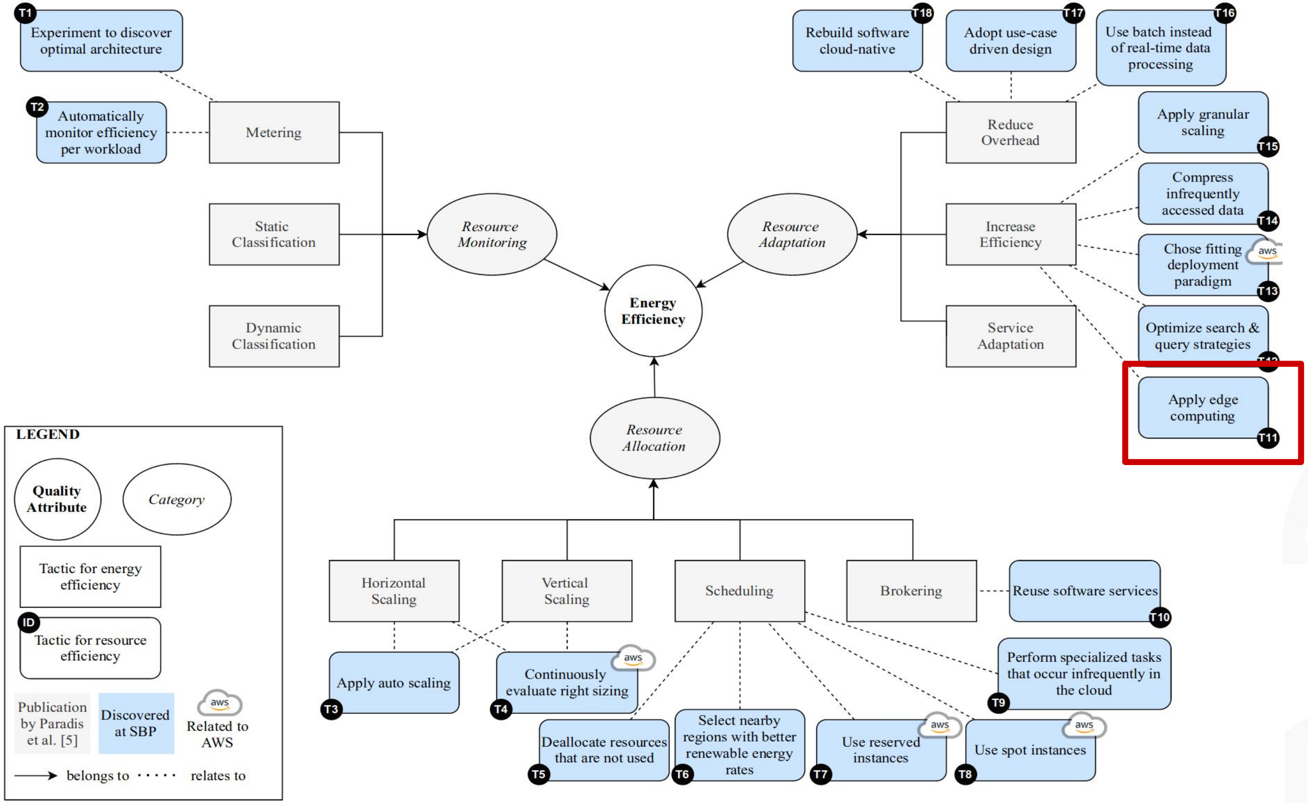
Reduced Latency

Energy Savings



Y. Li et al., "End-to-end energy models for Edge Cloud-based IoT platforms: Application to data stream analysis in IoT" . Future Generation Computer Systems
Procaccianti et. al, "Green Architectural Tactics for the Cloud", 2014 IEEE/IFIP Conference on Software Architecture, Sydney, Australia, 2014

Green Architectural Tactics for the Cloud



S. Vos, P. Lago, R. Verdecchia and I. Heitlager, "Architectural Tactics to Optimize Software for Energy Efficiency in the Public Cloud", 2022 International Conference on ICT for Sustainability (ICT4S), Plovdiv, Bulgaria, 2022

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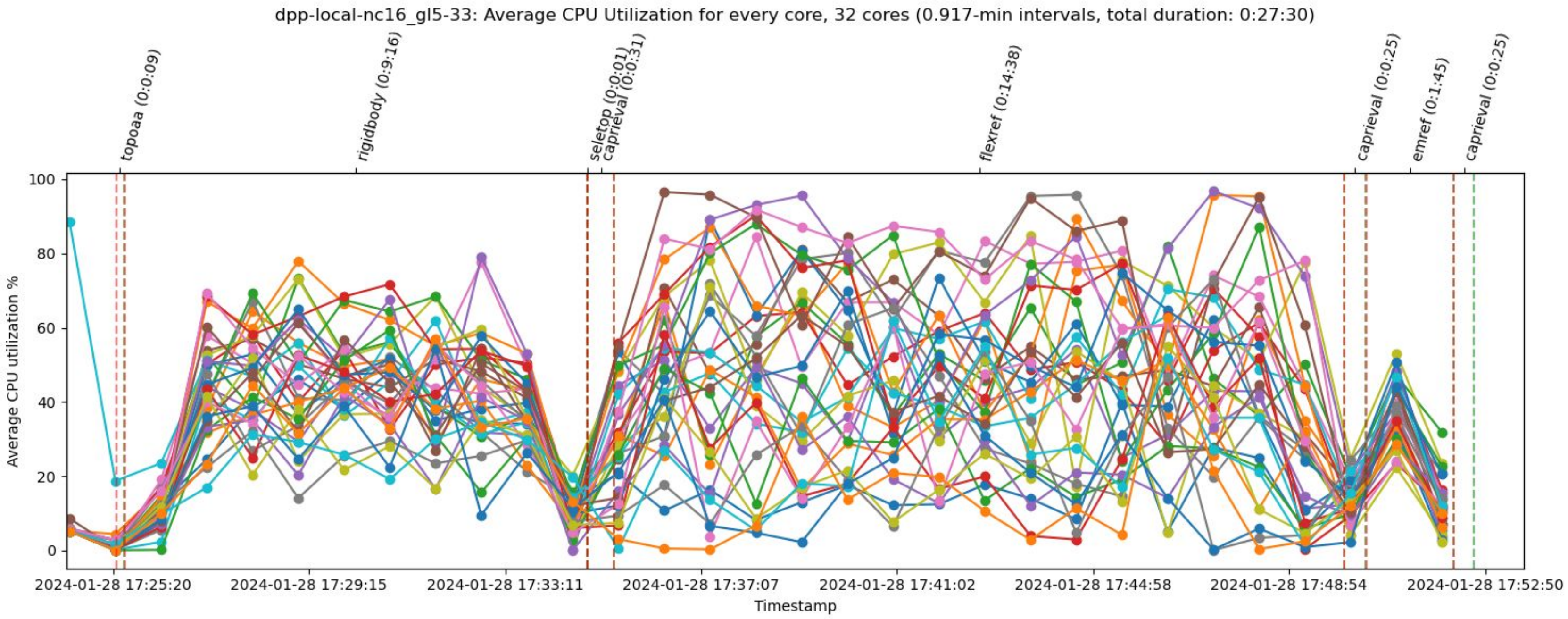
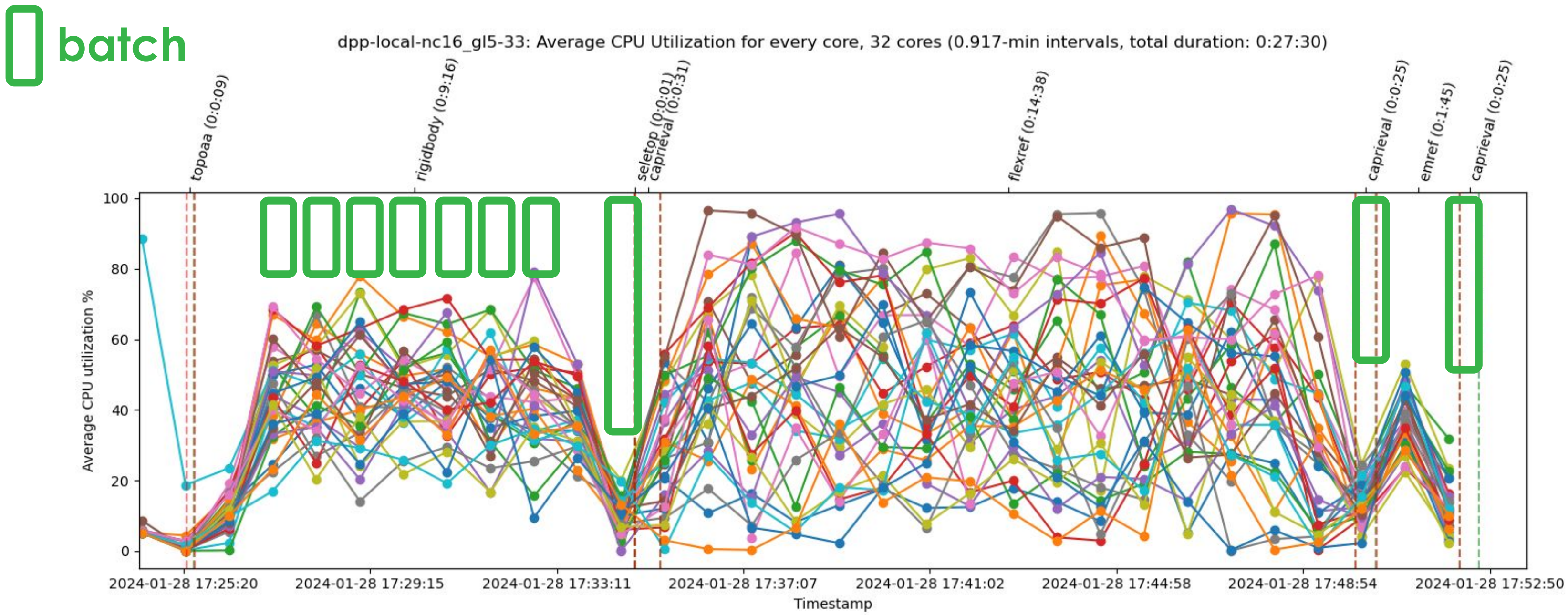
Tactic: Adaptive Batch Size Adjustment



Tactic: Adaptive Batch Size Adjustment



Outline

- Energy Efficiency Across **Programming Languages**
- Empirical Evaluation of **Two Best Practices** for Energy-Efficient Software Development

Measurement-Based

- Catalog of **Energy Patterns** for **Mobile** Applications

Data Mining

- An Approach Using Performance **Models** for Supporting Energy Analysis of Software Systems

Model-Based

Energy Efficiency Across Programming Languages

Energy Efficiency across Programming Languages

How Do Energy, Time, and Memory Relate?

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Abstract

This paper presents a study of the runtime, memory usage and energy consumption of twenty seven well-known software languages. We monitor the performance of such languages using ten different programming problems, expressed in each of the languages. Our results show interesting findings, such as, slower/faster languages consuming less/more energy, and how memory usage influences energy consumption. We show how to use our results to provide software engineers support to decide which language to use when energy efficiency is a concern.

CCS Concepts • **Software and its engineering → Software performance**; **General programming languages**;

Keywords Energy Efficiency, Programming Languages, Language Benchmarking, Green Software

ACM Reference Format:
Rui Pereira, Marco Couto, Francisco Ribeiro, Rui Rua, Jácome Cunha, João Paulo Fernandes, and João Saraiva. 2017. Energy Efficiency across Programming Languages: How Do Energy, Time, and Memory Relate?. In *Proceedings of 2017 ACM SIGPLAN International Conference on Software Language Engineering (SLE'17)*. ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3136014.3136031

1 Introduction

productivity - by incorporating advanced features in the language design, like for instance powerful modular and type systems - and at efficiently execute such software - by developing, for example, aggressive compiler optimizations. Indeed, most techniques were developed with the main goal of helping software developers in producing faster programs. In fact, in the last century *performance* in software languages was in almost all cases synonymous of *fast execution time* (embedded systems were probably the single exception).

In this century, this reality is quickly changing and software energy consumption is becoming a key concern for computer manufacturers, software language engineers, programmers, and even regular computer users. Nowadays, it is usual to see mobile phone users (which are powerful computers) avoiding using CPU intensive applications just to save battery/energy. While the concern on the computers' energy efficiency started by the hardware manufacturers, it quickly became a concern for software developers too [28]. In fact, this is a recent and intensive area of research where several techniques to analyze and optimize the energy co[...] sumption of software systems are being developed. [...] techniques already provide knowledge on the ene[...] ciency of data structures [15, 27] and android lan[...] the energy impact of different programming pr[...] mobile [18, 22, 31] and desktop applicatio[...]

	Energy
(c) C	1.00
(c) Rust	1.03
(c) C++	1.34
(c) Ada	1.70
(v) Java	1.98
(c) Pascal	2.14
(c) Chapel	2.18
(v) Lisp	2.27
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(i) JavaScript	4.45
(v) Racket	7.91
(i) TypeScript	21.50
(i) Hack	24.02
(i) PHP	29.30
(v) Erlang	42.23
(i) Lua	45.98
(i) Jruby	46.54
(i) Ruby	69.91
(i) Python	75.88
(i) Perl	79.58

Energy Efficiency Across Programming Languages

Motivation

Provide software engineers **support** to decide **which language** to use when energy **efficiency** is a concern

Method

Profile **10 well-known problems** implemented in **27 programming languages**

Research Questions

RQ1 Can we *compare* energy efficiency of SW languages?

RQ2 Is the *faster* language always the *most energy efficient*?

RQ3 How does (peak) *memory usage* relates to energy consumption?

RQ4 Can we *automatically decide* the *best* SW language considering *execution time*, *energy consumption*, *memory*?

RQ1: Can we *compare*?

CLBG is a **framework** for running, testing and comparing programming languages

Born in 00s for comparing scripting languages. Nowadays, it includes **13 problems** implemented in 28 programming languages

fannkuch-redux

source	secs	mem	gz	cpu secs
C++ g++ #6	3.23	10,936	1528	12.80
Rust #6	3.51	11,036	1253	13.93
C++ g++ #7	14.04	10,912	1150	14.04
Rust #4	7.21	10,932	1020	28.34

Benchmark	Description
n-body	Double precision N-body simulation
fannkuch-redux	Indexed access to tiny integer sequence
spectral-norm	Eigenvalue using the power method
mandelbrot	Generate Mandelbrot set portable bitmap file
pidigits	Streaming arbitrary precision arithmetic
regex-redux	Match DNA 8mers and substitute magic patterns
fasta	Generate and write random DNA sequences
k-nucleotide	Hashtable update and k-nucleotide strings
reverse-complement	Read DNA sequences, write their reverse-complement
binary-trees	Allocate, traverse and deallocate many binary trees
chameneos-redux	Symmetrical thread rendezvous requests
meteor-contest	Search for solutions to shape packing puzzle
thread-ring	Switch from thread to thread passing one token

Computer Language Benchmarks Game (CLBG), https://benchmarksgame-team.pages.debian.net/benchmarksgame/index.html, Accessed 09-09-2023

Experiment Design and Execution

- **Most efficient version** (i.e. fastest) version of the source code
- Replicated **the information** of the CLBG
- **Functional Correctness** Verification
- Each benchmark has been executed 10 times
- **Peak Memory Usage** measured with using `/usr/bin/time -v command`

```
...
for (i = 0 ; i < N ; i++){
  time_before = getTime(...);
  //performs initial energy measurement
  rapl_before(...);

  //executes the program
  system(command);

  //computes the difference between
  //this measurement and the initial one
  rapl_after(...);
  time_elapsed = getTime(...) - time_before;
  ...
}
...
```

Figure: Measurement Framework

RQ2: Is Faster, Greener?

No, a faster language is **not always** the most energy efficient

- Energy (J) = Power (W) x Time (s)

Fastest and most *Energy Efficient* Languages:

- Compiled
- Imperative

87-88% of the energy consumption **derived from the CPU** and the remaining to the DRAM

fasta				
	Energy	Time	Ratio	Mb
(c) Rust $\Downarrow_9$	26.15	931	0.028	16
(c) Fortran $\downarrow_6$	27.62	1661	0.017	1
(c) C $\uparrow_1$ $\Downarrow_1$	27.64	973	0.028	3
(c) C++ $\uparrow_1$ $\Downarrow_2$	34.88	1164	0.030	4
(v) Java $\uparrow_1$ $\Downarrow_{12}$	35.86	1249	0.029	41
(c) Swift $\Downarrow_9$	37.06	1405	0.026	31
(c) Go $\downarrow_2$	40.45	1838	0.022	4
(c) Ada $\downarrow_2$ $\Uparrow_3$	40.45	2765	0.015	3
(c) Ocaml $\downarrow_2$ $\Downarrow_{15}$	40.78	3171	0.013	201
(c) Chapel $\uparrow_5$ $\Downarrow_{10}$	40.88	1379	0.030	53
(v) C# $\uparrow_4$ $\Downarrow_5$	45.35	1549	0.029	35
(i) Dart $\Downarrow_6$	63.61	4787	0.013	49
(i) JavaScript $\Downarrow_1$	64.84	5098	0.013	30
(c) Pascal $\downarrow_1$ $\Uparrow_{13}$	68.63	5478	0.013	0
(i) TypeScript $\downarrow_2$ $\Downarrow_{10}$	82.72	6909	0.012	271
(v) F# $\uparrow_2$ $\Uparrow_3$	93.11	5360	0.017	27
(v) Racket $\downarrow_1$ $\Uparrow_5$	120.90	8255	0.015	21
(c) Haskell $\uparrow_2$ $\Downarrow_8$	205.52	5728	0.036	446
(v) Lisp $\Downarrow_2$	231.49	15763	0.015	75
(i) Hack $\Downarrow_3$	237.70	17203	0.014	120
(i) Lua $\Uparrow_{18}$	347.37	24617	0.014	3
(i) PHP $\downarrow_1$ $\Uparrow_{13}$	430.73	29508	0.015	14
(v) Erlang $\uparrow_1$ $\Uparrow_{12}$	477.81	27852	0.017	18
(i) Ruby $\downarrow_1$ $\Uparrow_2$	852.30	61216	0.014	104
(i) JRuby $\uparrow_1$ $\Downarrow_2$	912.93	49509	0.018	705
(i) Python $\downarrow_1$ $\Uparrow_{18}$	1,061.41	74111	0.014	9
(i) Perl $\uparrow_1$ $\Uparrow_8$	2,684.33	61463	0.044	53

Energy Efficiency Across Programming Languages, https://sites.google.com/view/energy-efficiency-languages, Accessed 09-09-2023

RQ3: Memory Impact on Energy

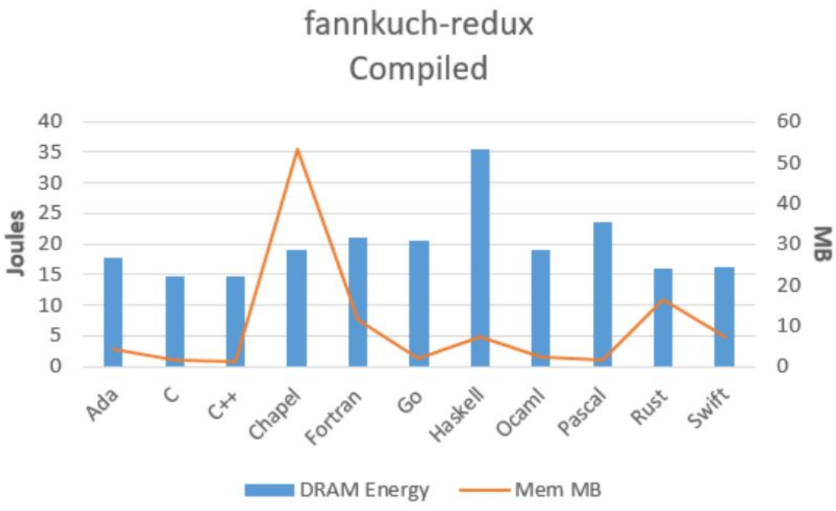
Peak memory usage: highest point of memory consumption reached by a program throughout its runtime

Best Languages:

- Imperative
- Compiled

No correlation between *DRAM energy consumption* and *peak memory usage*

ToDo: correlation between energy consumption and *continuous memory usage*



RQ4: Energy vs Time vs Memory

Time & Memory	Energy & Time	Energy & Memory	Energy & Time & Memory
C • Pascal • Go	C	C • Pascal	C • Pascal • Go
Rust • C++ • Fortran	Rust	Rust • C++ • Fortran • Go	Rust • C++ • Fortran
Ada	C++	Ada	Ada
Java • Chapel • Lisp • Ocaml	Ada	Java • Chapel • Lisp	Java • Chapel • Lisp • Ocaml
Haskell • C#	Java	OCaml • Swift • Haskell	Swift • Haskell • C#
Swift • PHP	Pascal • Chapel	C# • PHP	Dart • F# • Racket • Hack • PHP
F# • Racket • Hack • Python	Lisp • Ocaml • Go	Dart • F# • Racket • Hack • Python	JavaScript • Ruby • Python
JavaScript • Ruby	Fortran • Haskell • C#	JavaScript • Ruby	TypeScript • Erlang
Dart • TypeScript • Erlang	Swift	TypeScript	Lua • JRuby • Perl
JRuby • Perl	Dart • F#	Erlang • Lua • Perl	
Lua	JavaScript	JRuby	
	Racket		
	TypeScript • Hack		
	PHP		
	Erlang		
	Lua • JRuby		
	Ruby		

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Summary

- **Comparable?**
- ***Compiled and Imperative*** programming language **perform better** and **more energy/memory efficient**
- *(RQ3)* It is not possible to find a programming language that **improves all three attributes**
- **CPU** seems consuming most of the **energy consumption**
- *(RQ2)* An evaluation of memory usage over time **is missing**

	Energy
(c) C	1.00
(c) Rust	1.03
(c) C++	1.34
(c) Ada	1.70
(v) Java	1.98
(c) Pascal	2.14
(c) Chapel	2.18
(v) Lisp	2.27
(c) Ocaml	2.40
(c) Fortran	2.52
(c) Swift	2.79
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(i) PHP	29.30
(v) Erlang	42.23
(i) Lua	45.98
(i) Jruby	46.54
(i) Ruby	69.91
(i) Python	75.88
(i) Perl	79.58

	Time
(c) C	1.00
(c) Rust	1.04
(c) C++	1.56
(c) Ada	1.85
(v) Java	1.89
(c) Chapel	2.14
(c) Go	2.83
(c) Pascal	3.02
(c) Ocaml	3.09
(v) C#	3.14
(v) Lisp	3.40
(c) Haskell	3.55
(c) Swift	4.20
(c) Fortran	4.20
(v) F#	6.30
(i) JavaScript	6.52
(i) Dart	6.67
(v) Racket	11.27
(i) Hack	26.99
(i) PHP	27.64
(v) Erlang	36.71
(i) Jruby	43.44
(i) TypeScript	46.20
(i) Ruby	59.34
(i) Perl	65.79
(i) Python	71.90
(i) Lua	82.91

	Mb
(c) Pascal	1.00
(c) Go	1.05
(c) C	1.17
(c) Fortran	1.24
(c) C++	1.34
(c) Ada	1.47
(c) Rust	1.54
(v) Lisp	1.92
(c) Haskell	2.45
(i) PHP	2.57
(c) Swift	2.71
(i) Python	2.80
(c) Ocaml	2.82
(v) C#	2.85
(i) Hack	3.34
(v) Racket	3.52
(i) Ruby	3.97
(c) Chapel	4.00
(v) F#	4.25
(i) JavaScript	4.59
(i) TypeScript	4.69
(v) Java	6.01
(i) Perl	6.62
(i) Lua	6.72
(v) Erlang	7.20
(i) Dart	8.64
(i) Jruby	19.84

Summary

- ***Compiled and Imperative*** programming language **perform better** and **more energy/memory efficient**

- It is not possible to find a programming language that **improves all three attributes**

- **CPU** seems consuming most of the **energy consumption**

- An evaluation of memory usage over time **is missing**

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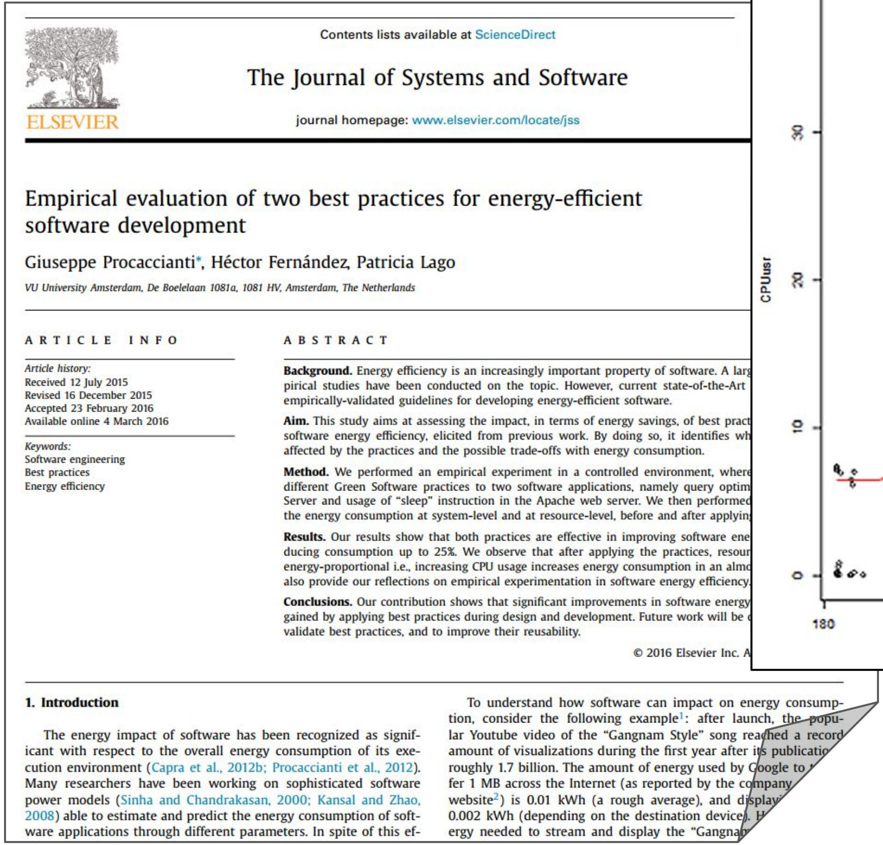
Empirical Evaluation of Two Best Practices for Energy-Efficient Software Development



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The Journal of Systems and Software

journal homepage: www.elsevier.com/locate/jss

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Empirical evaluation of two best practices for energy-efficient software development

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ARTICLE INFO

Article history:
Received 12 July 2015
Revised 16 December 2015
Accepted 23 February 2016
Available online 4 March 2016

Keywords:
Software engineering
Best practices
Energy efficiency

ABSTRACT

Background. Energy efficiency is an increasingly important property of software. A larg pirical studies have been conducted on the topic. However, current state-of-the-Art empirically-validated guidelines for developing energy-efficient software.

Aim. This study aims at assessing the impact, in terms of energy savings, of best pract software energy efficiency, elicited from previous work. By doing so, it identifies wh affected by the practices and the possible trade-offs with energy consumption.

Method. We performed an empirical experiment in a controlled environment, where different Green Software practices to two software applications, namely query optim Server and usage of "sleep" instruction in the Apache web server. We then performed the energy consumption at system-level and at resource-level, before and after applyin

Results. Our results show that both practices are effective in improving software ene ducing consumption up to 25%. We observe that after applying the practices, resour energy-proportional i.e., increasing CPU usage increases energy consumption in an almo also provide our reflections on empirical experimentation in software energy efficiency.

Conclusions. Our contribution shows that significant improvements in software energy gained by applying best practices during design and development. Future work will be validate best practices, and to improve their reusability.

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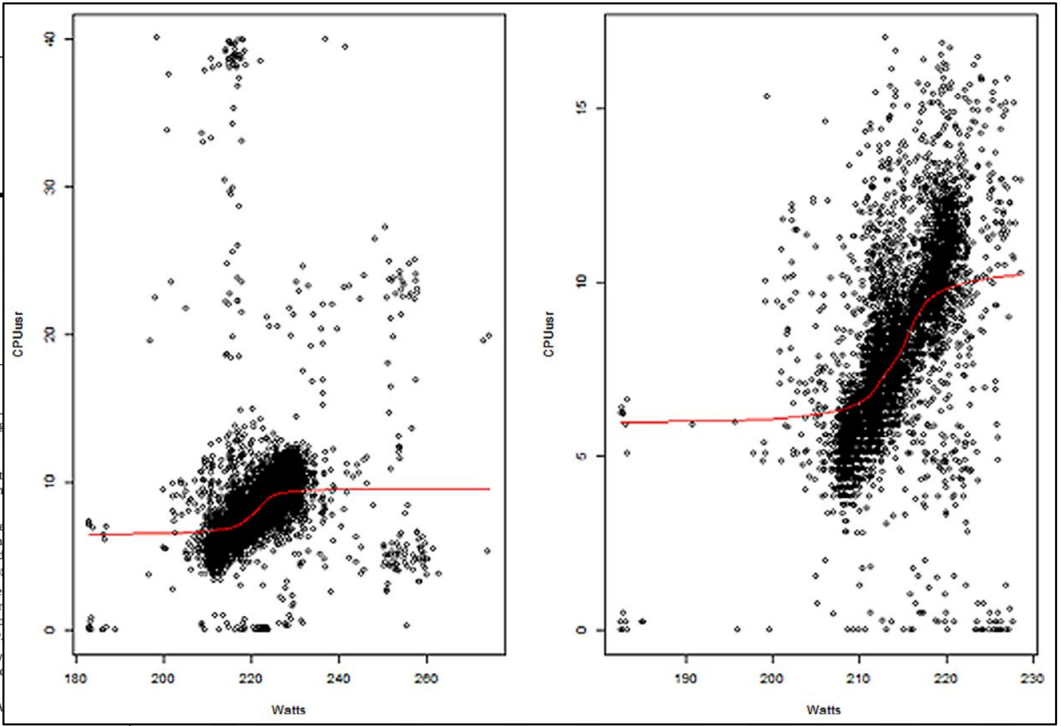
1. Introduction

The energy impact of software has been recognized as significant with respect to the overall energy consumption of its execution environment (Capra et al., 2012b; Procaccianti et al., 2012). Many researchers have been working on sophisticated software power models (Sinha and Chandrakasan, 2000; Kansal and Zhao, 2008) able to estimate and predict the energy consumption of software applications through different parameters. In spite of this ef-

To understand how software can impact on energy consumption, consider the following example[1]: after launch, the popular Youtube video of the "Gangnam Style" song reached a record amount of visualizations during the first year after its publicatio roughly 1.7 billion. The amount of energy used by Google to fer 1 MB across the Internet (as reported by the company website[2]) is 0.01 kWh (a rough average), and displayi 0.002 kWh (depending on the destination device). H ergy needed to stream and display the "Gangnam



Empirical Evaluation of Two Best Practices for Energy-Efficient Software Development

Motivation

Current SoA does not provide **empirical evidence** of tactics for green software

Method

Controlled Experiment in which **two practices** were empirically evaluated

Research Questions

RQ1: What is the *impact of each practice* in terms of energy consumption?

RQ2: Is the *relationship* between *resources and power consumption* affected by the application of each practice?

Experiment Design

Two Practices: (1) *Put application to sleep* and (2) *Use Efficient Query*

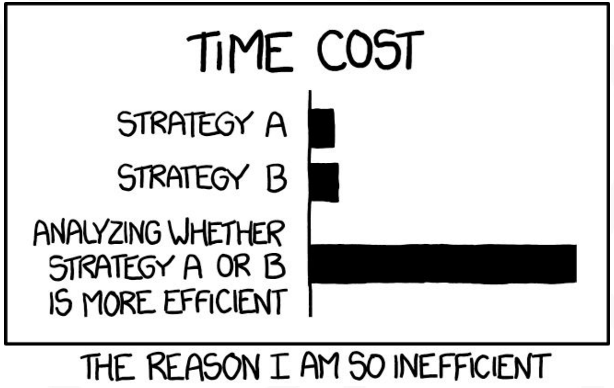
Practices **manually** applied to:

- *Apache Web Server* for (1)
- MySQL Database Server for (2)

Metrics:

- Energy Consumption at **System-Level**
- Energy Values of **Each Resource** (CPU, Disk, Network, Memory)

Goal: absence/application of each Green SW Practice



Source: https://xkcd.com/1445/

Experimental Setting

Blocked Factors:

- *Fixed* Workload (e.g., total number of requests, database size)
- *Fixed* Testbed (HW/SW)

Profilers:

- **Power:** Wattsup Pro, Data Acquisition (DAQ) boards
- **Metrics Aggregator**: Intel Energy Server (ESRV)
- **Resource Usage:** Dstat (also aggregator - e.g, vmstat, iostat)

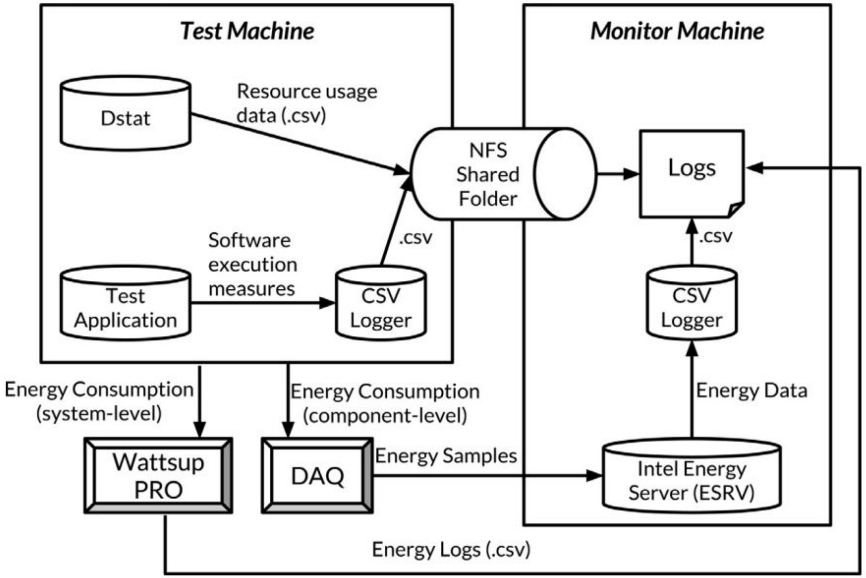


Figure: Experiment Setting

Experiment Execution

Practice 1: Use Efficient Queries:

- Database **populated** with the English Version of Wikipedia (30GB)
- **Query searching** for text fragments

```
SELECT SQL_NO_CACHE a.old_id
FROM text a, revision b
WHERE a.old_id = b.rev_text_id
ORDER BY a.old_id;
```

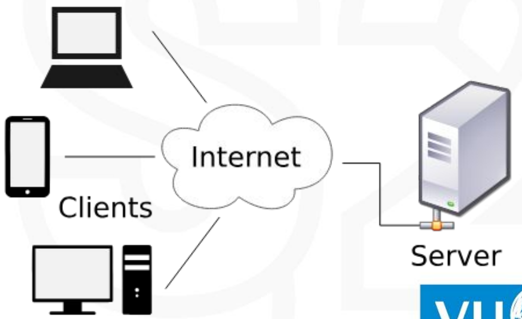
Figure: Query before applying the practice

```
SELECT SQL_NO_CACHE a.old_id
FROM text a, revision b
WHERE a.old_id = b.rev_text_id
```

Figure: Query after applying the practice

Practice 2: Put Application to Sleep

- `sleep()` while waiting for a HTTP Request
- Workload made of **5 million** requests with **max 50 concurrent requests** and a time limit of **5 min** (ab utility)



Efficient Query - Results

RQ1: What is the <u>impact of each practice</u> in terms of energy consumption?

- *Low decrease* in **Power Consumption** due to *performance optimization*

RQ2: Is the relationship between <u>resources and power consumption</u> affected by the application of each practice?

- *Correlation* between *CPU and Disk Consumption* (after)
- The *correlation I/O operations* and energy have ***negative correlation*** (CPU Inactive)

```
SELECT SQL_NO_CACHE a.old_id
FROM text a, revision b
WHERE a.old_id = b.rev_text_id
ORDER BY a.old_id;
```

Figure: Query before applying the practice

```
SELECT SQL_NO_CACHE a.old_id
FROM text a, revision b
WHERE a.old_id = b.rev_text_id
```

Figure: Query after applying the practice

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Put Application to Sleep

RQ1: What is the <u>impact of each practice</u> in terms of energy consumption?

- Almost **no difference between Power and Energy Consumption Improvement** (correlation between performance and energy)

RQ2: Is the relationship between <u>resources and power consumption</u> affected by the application of each practice?

- Confirmed *Energy-Proportional* Behavior
- CPU not the main driver of energy consumption, *memory* has <u>*the same consumption*</u>

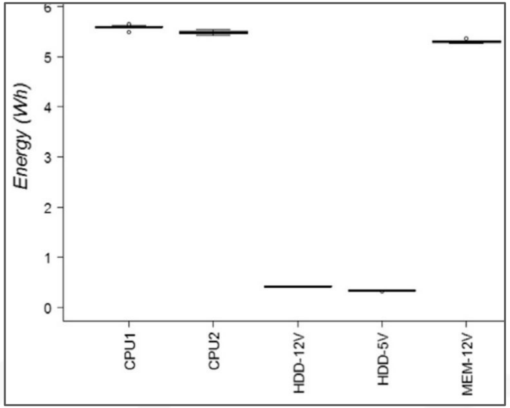

Figure: Energy Consumption *before* applying the practice

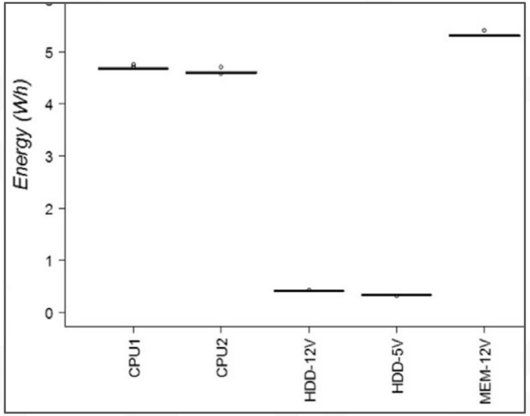

Figure: Energy Consumption *after* applying the practice

Summary

- The paper confirms the **importance** of Green Software Tactics
  - **Significant Energy Reduction (25%)**
  - **Impact** of Resource Consumption
- Energy Consumption should be considered **a first-class design concern**

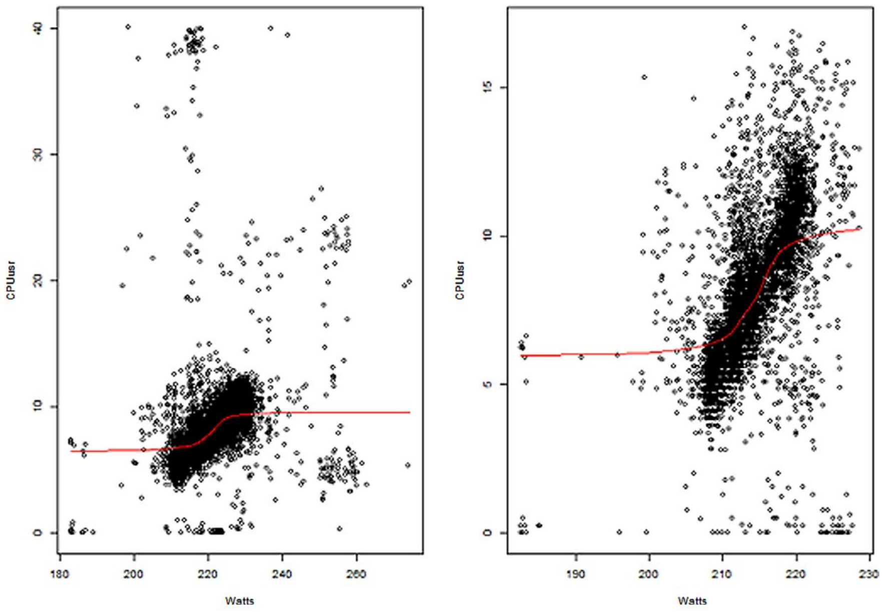

Figure: CPU utilization and CPU Energy Consumption before and after applying Practice 1

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Outline

- Energy Efficiency Across **Programming Languages**
- Empirical Evaluation of **Two Best Practices** for Energy-Efficient Software Development

Measurement-Based

- Catalog of **Energy Patterns** for **Mobile** Applications

Data Mining

- An Approach Using Performance **Models** for Supporting Energy Analysis of Software Systems

Model-Based

Catalog of Energy Patterns for Mobile Applications

Home > Empirical Software Engineering > Article

Published: 05 March 2019

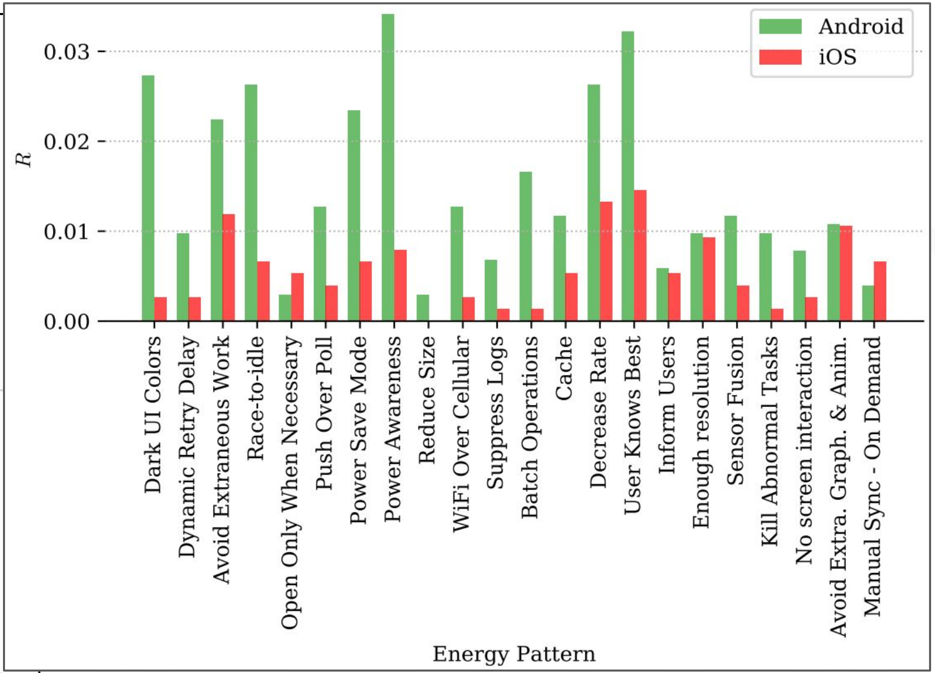
Catalog of energy patterns for mobile applications

Luis Cruz & Rui Abreu

Empirical Software Engineering **24**, 2209–2235 (2019) | Cite this article

Abstract

Software engineers make use of design patterns for reasons that range from performance to code comprehensibility. Several design patterns capturing the body of knowledge of best practices have been proposed in the past, namely creational, structural and behavioral patterns. However, with the advent of mobile devices, it becomes a necessity a catalog of design patterns for energy efficiency. In this work, we inspect commits, issues and pull requests of 1027 Android and 756 iOS apps to identify common practices when improving energy efficiency. This analysis yielded a catalog, available online, with 22 design patterns related to improving the energy efficiency of mobile apps. We argue that this catalog might be of relevance to other domains such as Cyber-Physical Systems and Internet of Things. As a side contribution, an analysis of the differences between Android and iOS devices shows that the Android community is more energy-aware.

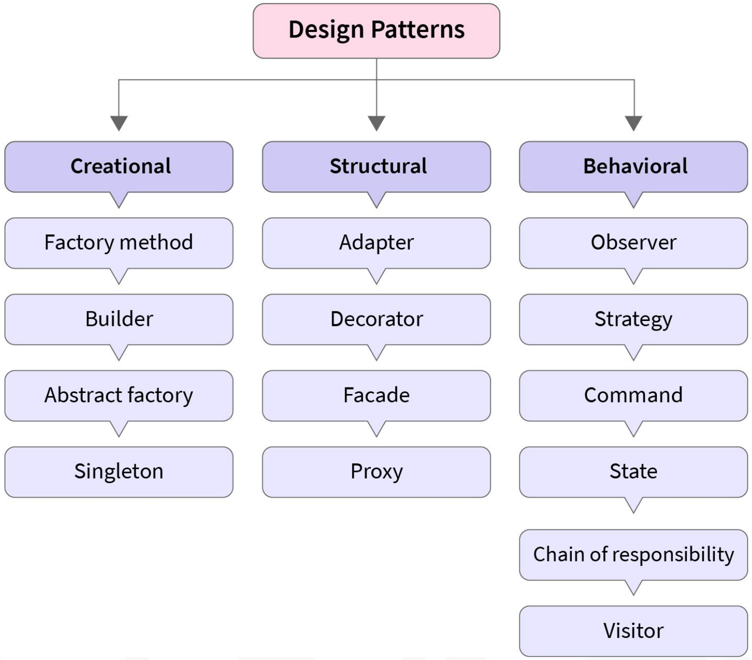


Catalog of Energy Patterns for Mobile Applications

Motivation

The adoption of ***design patterns*** is widespread across software developers, e.g., to **avoid performance bottlenecks and increase comprehensibility**

> *Design Pattern:* Each pattern describes a ***recurrent*** design problem, its **solution** and the **consequences** of applying it



IMG: https://www.scaler.com/topics/design-patterns/types-of-design-pattern/

Method

Mining software repositories: inspect *commits*, *issues* and *pull* requests on GitHub

Gamma, E., Helm, R., Johnson, R., & Vlissides, J. (1995), *Design patterns: elements of reusable object-oriented software*, Pearson Deutschland

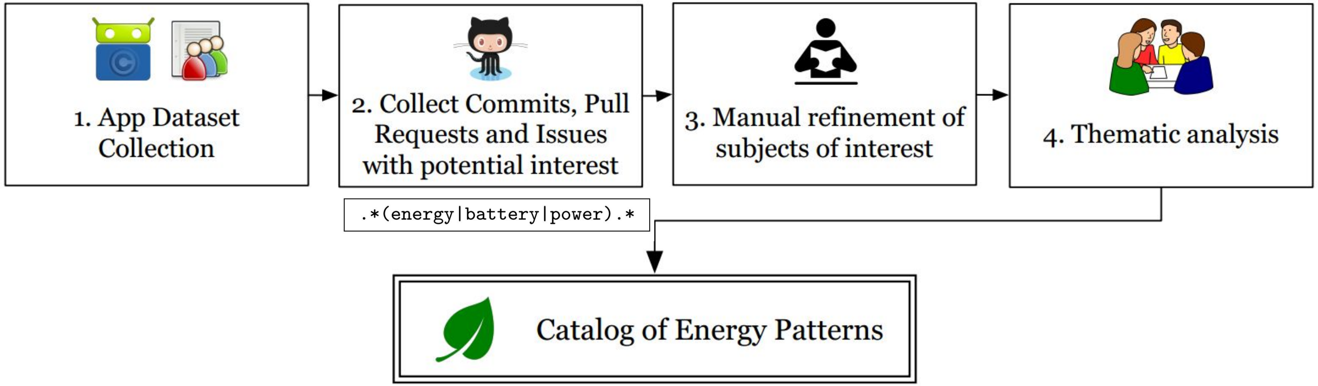
Catalog of Energy Patterns for Mobile Applications

Research Questions

RQ1: Which *design patterns* do mobile app developers ***adopt*** to *improve energy efficiency*?

RQ2: How different are *mobile app practices addressing energy efficiency* **across** different **platforms**?

App Dataset: *1027* Android apps (F-Droid) and *756* iOS apps (Collaborative List of Open-Source iOS Apps)



Subjects: 1563
Commits: 332
Issues: 1089
Pull Requests: 142
Patterns: 22 in 431 subjects

Gamma, E., Helm, R., Johnson, R., & Vlissides, J. (1995), *Design patterns: elements of reusable object-oriented software*, Pearson Deutschland

Dataset Collection

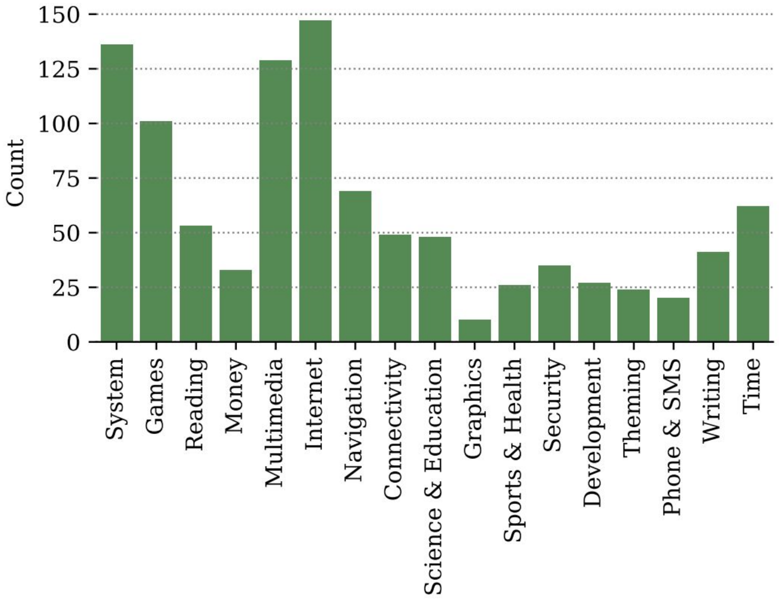


Figure: Android Applications Categories

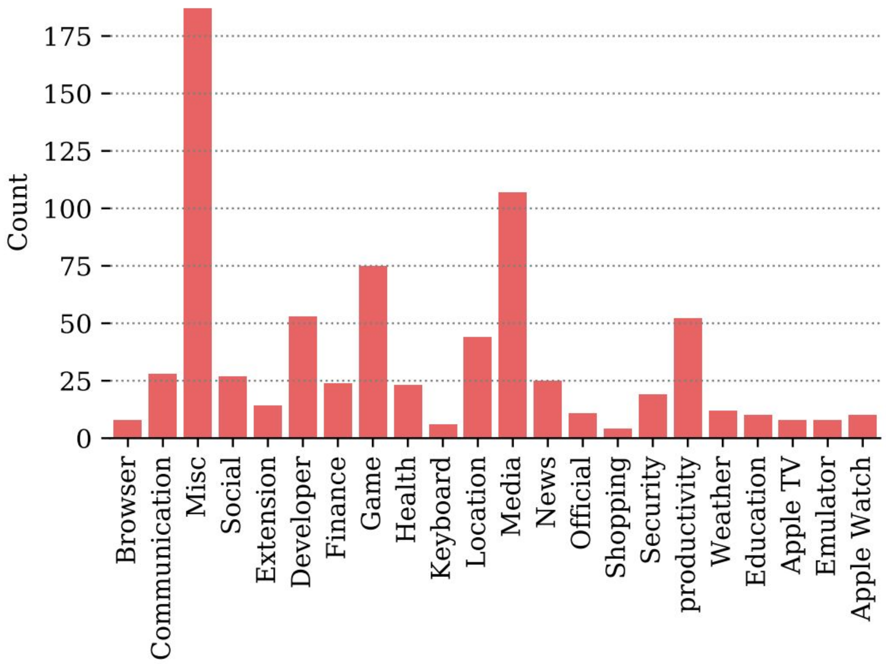


Figure: iOS Application Categories

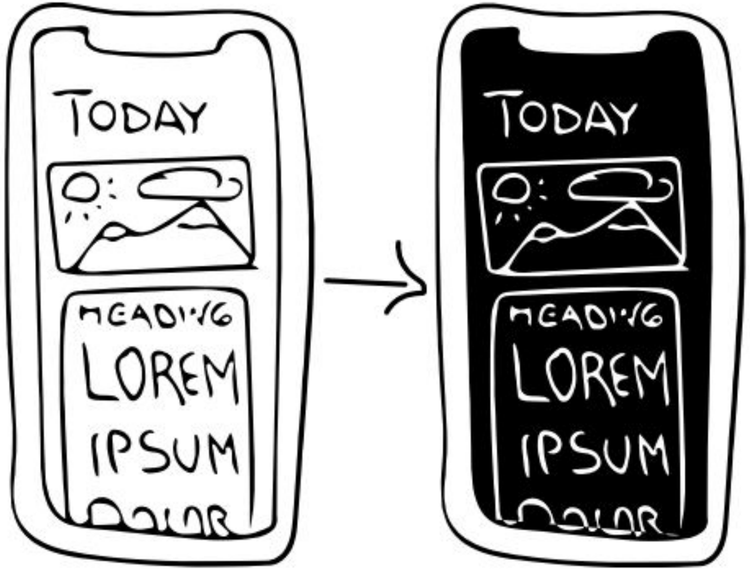
1. https://f-droid.org/
2. https://github.com/dkhamsing/open-source-ios-apps

Dark UI Colors

Context:
Apps that require heavy usage of screen (e.g., reading apps) can have a substantial negative impact on battery life

Solution:
Provide a UI with dark background colors

Example:
Provide a theme with a dark background using light colors to display text.

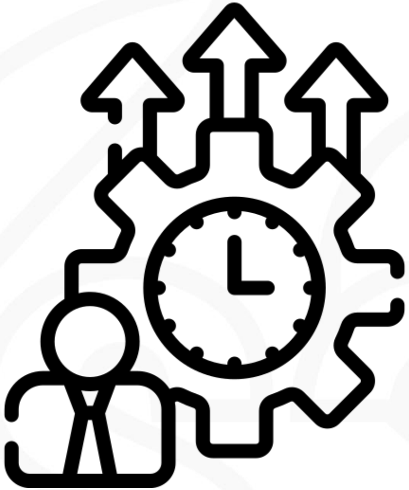


Dynamic Retry Delay

Context:
A resource is unavailable, the app will unnecessarily try to connect the resource for a number of times, leading to unnecessary power consumption.

Solution:
Increase retry interval after each failed connection

Example:
Instead of continuously polling the server until the server is available, use the Fibonacci series to increase the time between attempts

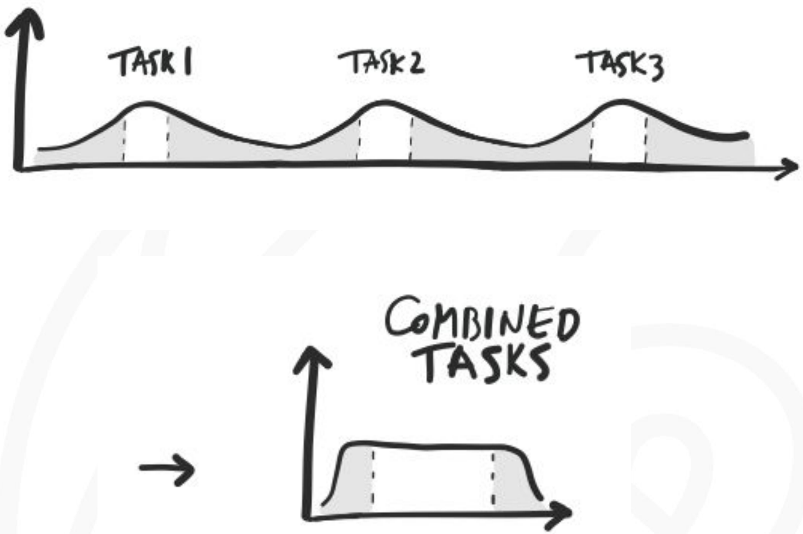


Batch Operations

Context:
Executing operations separately leads to extraneous tail energy consumptions

Solution:
Bundle multiple operations in a single one. By combining multiple tasks, tail energy consumptions can be optimized

Example:
Use Job Scheduling APIs (e.g., 'android.app.job.JobScheduler', 'Firebase JobDispatcher') that manage multiple background tasks occurring in a device.



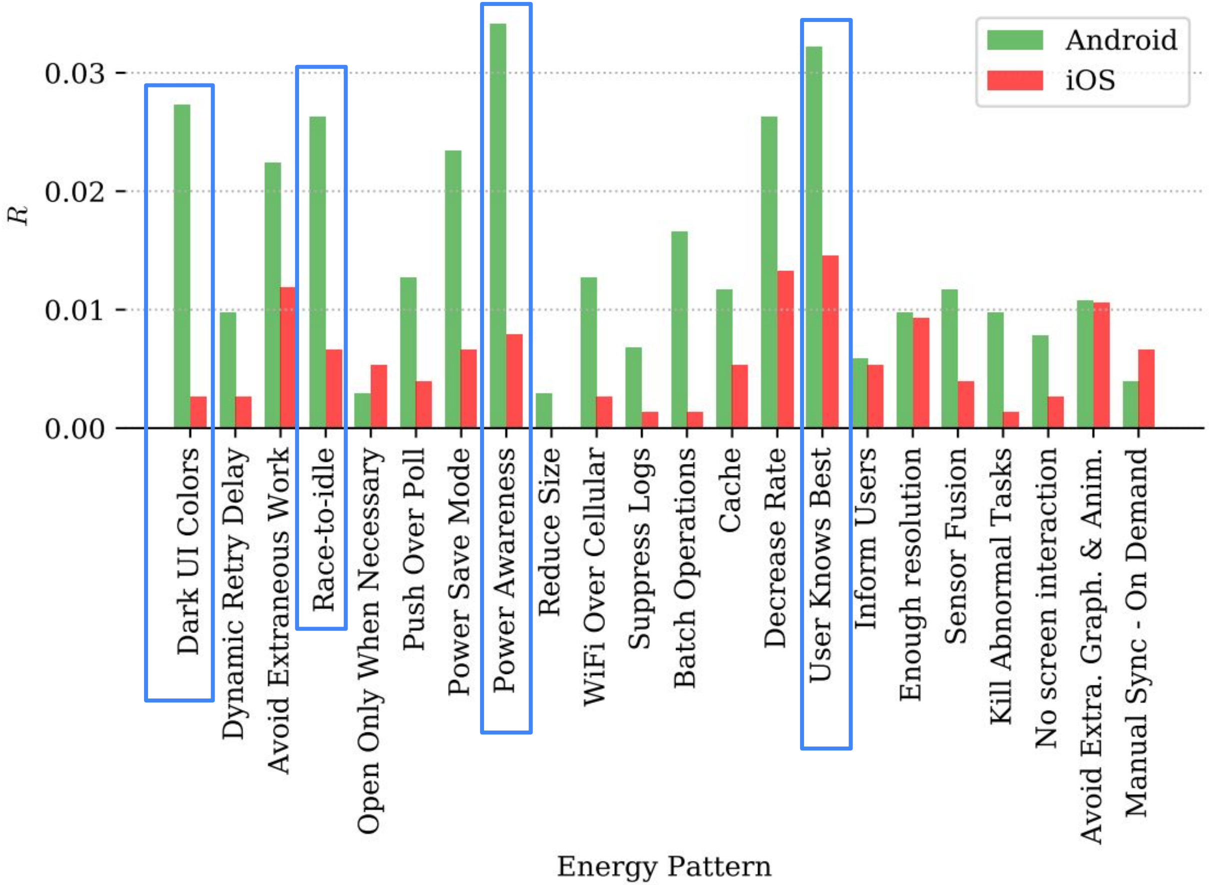
Cache

Context:
Same data is being collected from the server multiple times

Solution:
Implement caching mechanisms to temporarily store data from a server

Example:
Instead of downloading basic information and profile pictures every time a given profile is opened, the app can use data that was locally stored from earlier visits

Energy Patterns Frequency



Insights

- **Patterns** found in 133 Android apps (13%) and 28 iOS apps (4%)
  - Reasons not deeply discussed in the study (App Store constraints)
- **Characteristics** of the **applications** can have **influenced** the results
  - Sample unbalanced
  - Technology (e.g., AMOLED Screen)
  - APIs Features (e.g., Batch Operations in Android)
- *There is no empirical study that has evaluated the cost and benefit of applying these patterns*

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Model-Based

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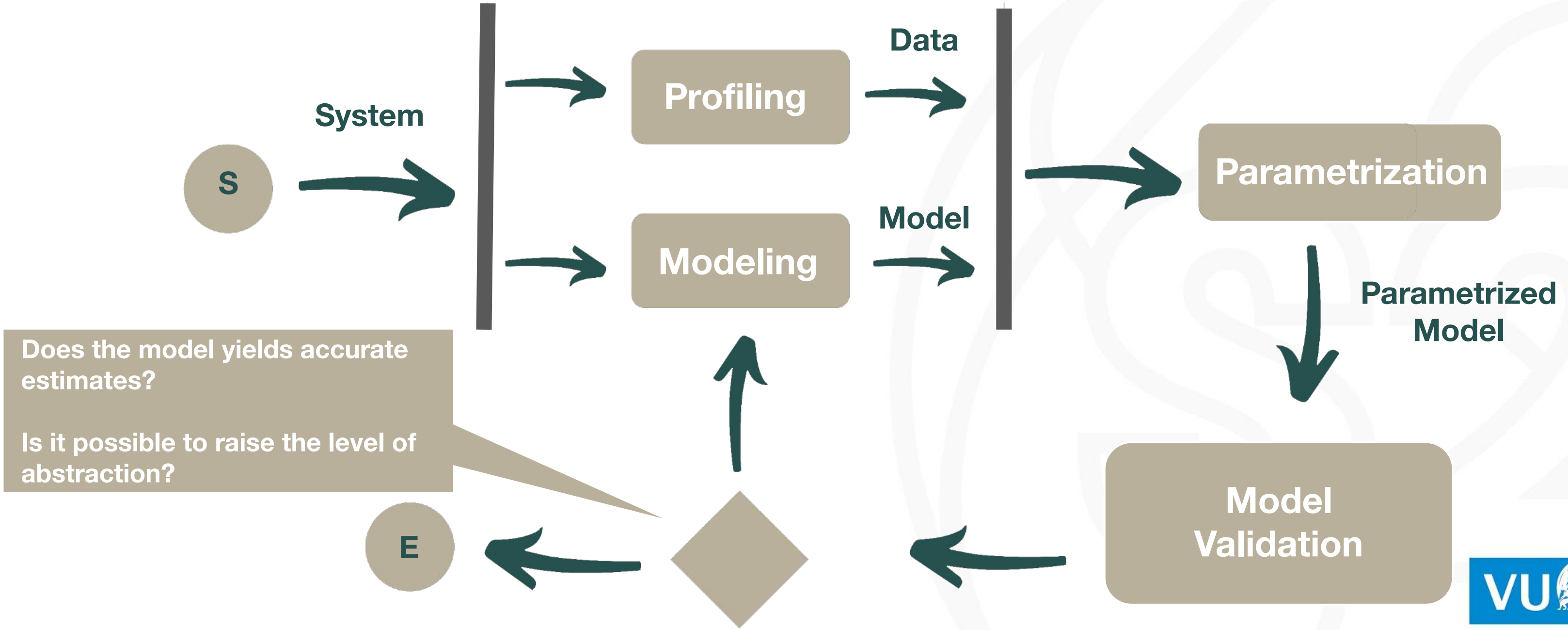
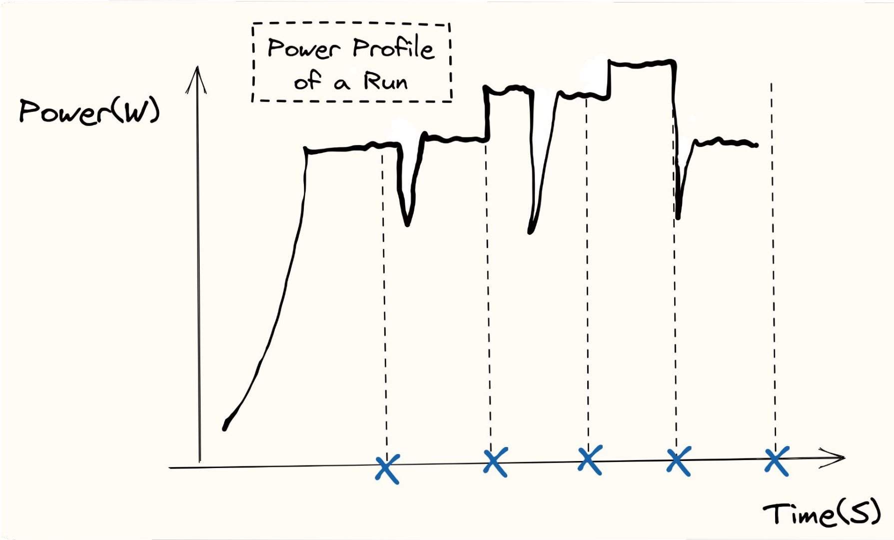
Reducing the Reality Gap

Explore the ***combination*** of measurement-based experiments and modeling in the context of ***energy/performance*** *analysis* of software systems

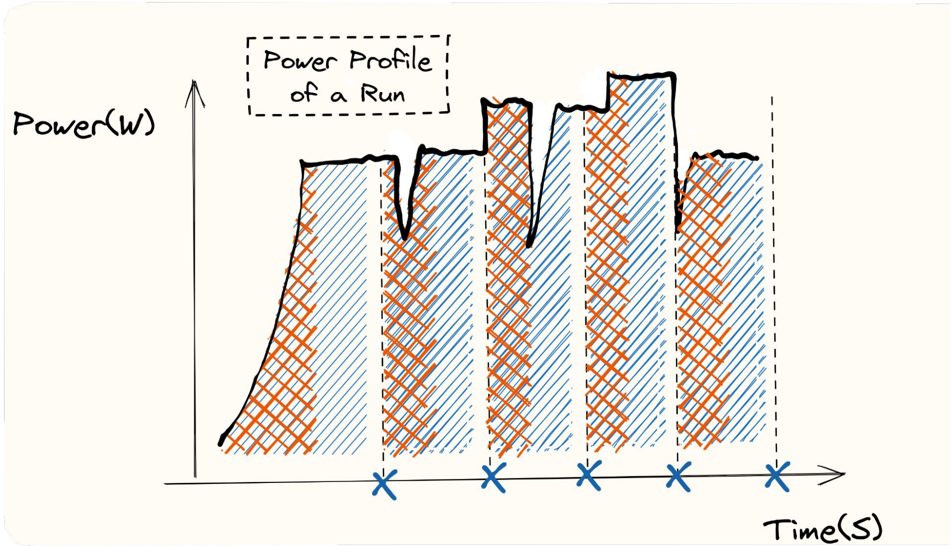


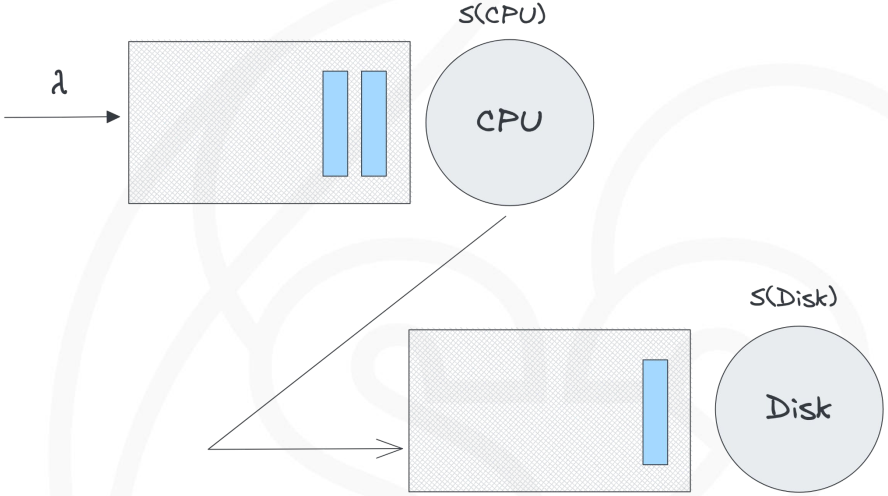
Power Profile



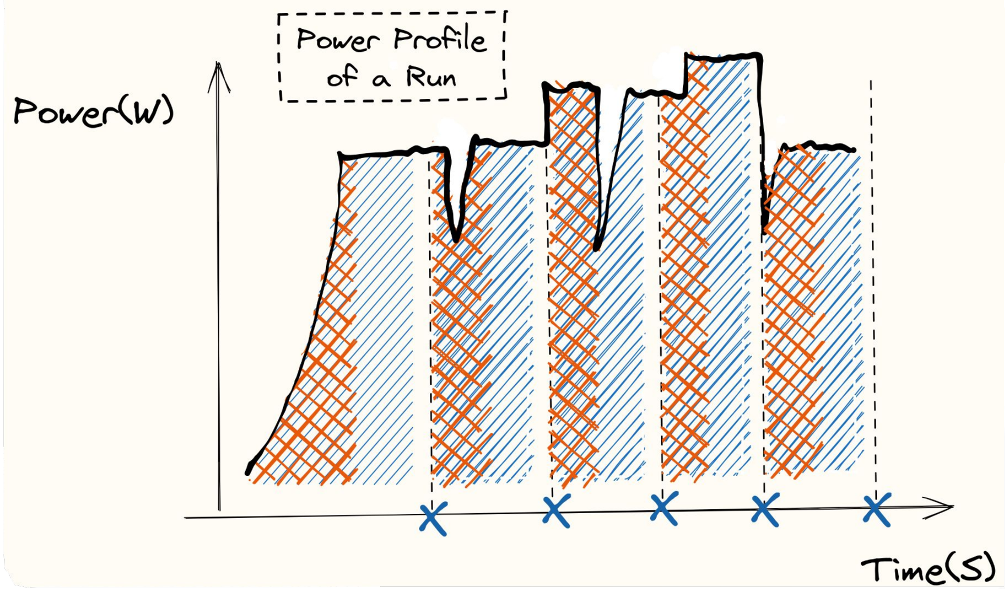
1. Behavior(Model) ~ Behavior(System)
2. Behavior → PowerProfile
3. PowerProfile(System) ~ PowerProfile(Model)

Queuing Networks





Resources Average Power Consumption



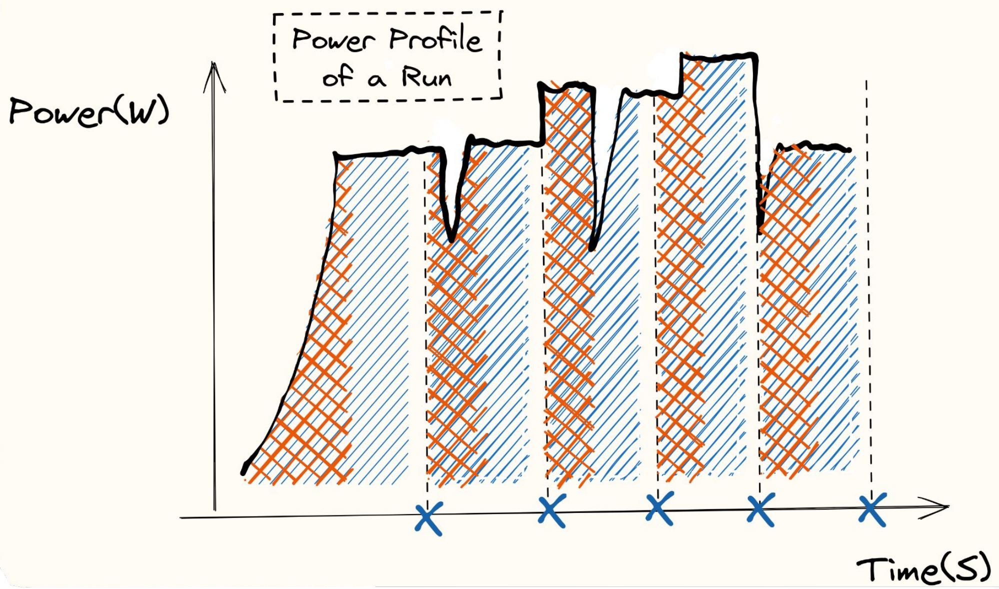
$$E(res, i) = \int_{t0,i}^{S_{res}} P(t)\, dt [\frac{Joule}{Visit}] \quad (1)$$

CPU-Time

Disk-Time

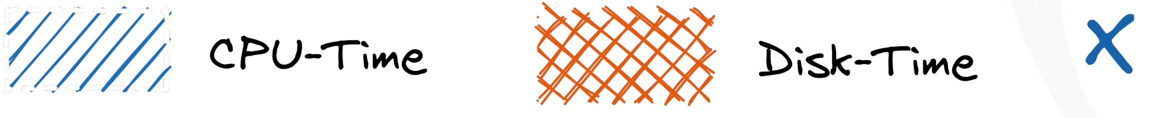
X Observation Time

Resources Average Power Consumption

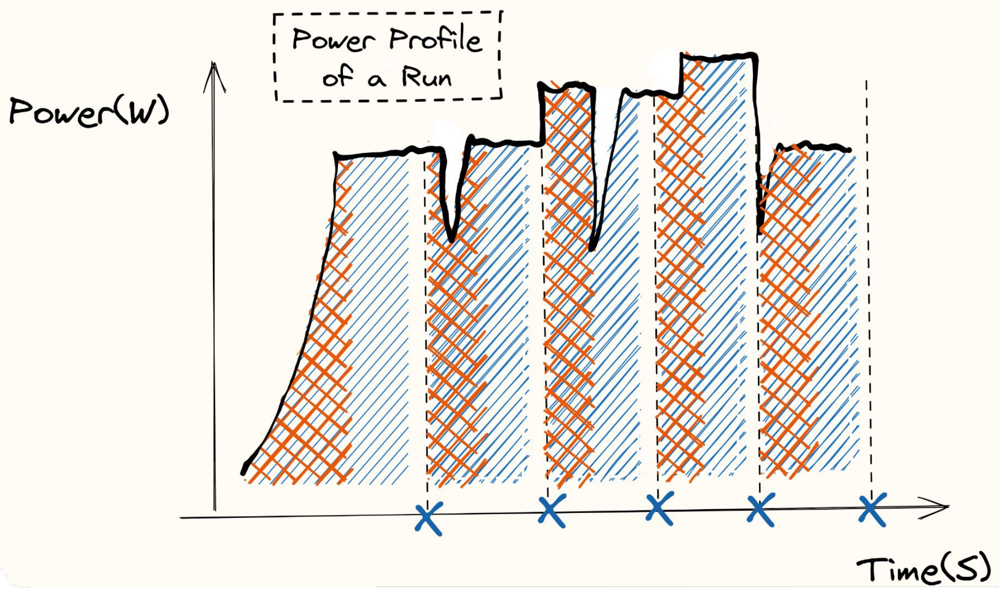


$$E(res, i) = \int_{t0,i}^{S_{res}} P(t)\, dt[\frac{Joule}{Visit}] \quad (1)$$

$$ED(res) = \sum_{i=1}^{\#Visit} \int_{t0,i}^{S_{res,i}} P(t)\, dt[Joule] \quad (2)$$



Resources Average Power Consumption



$$E(res, i) = \int_{t0,i}^{S_{res}} P(t)\, dt[\frac{Joule}{Visit}] \quad (1)$$

$$ED(res) = \sum_{i=1}^{\#Visit} \int_{t0,i}^{S_{res,i}} P(t)\, dt[Joule] \quad (2)$$

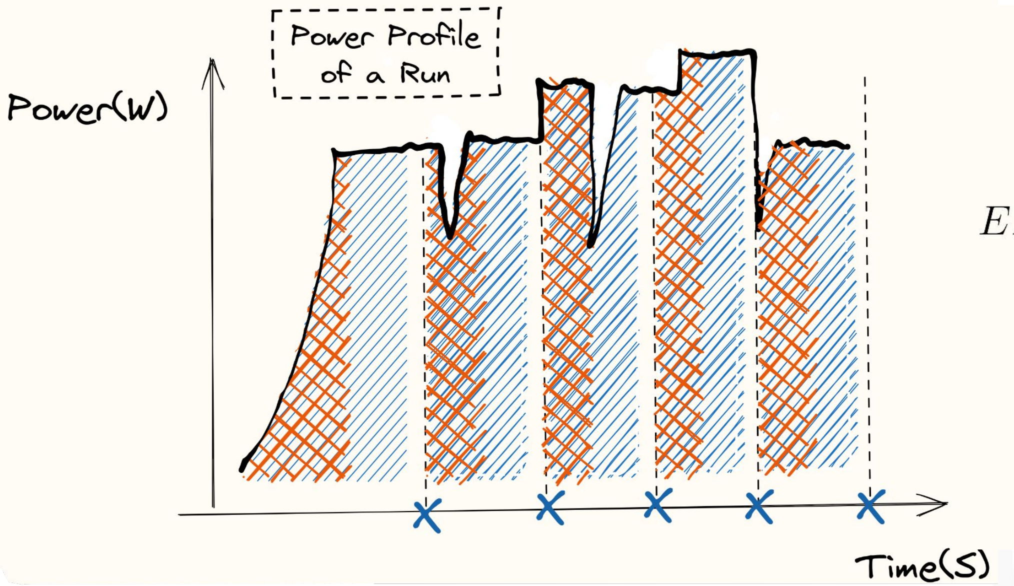
$$E(res) = \frac{ED(res)}{\#Visit}[\frac{Joule}{Visit}] \quad (3)$$

CPU-Time

Disk-Time

Observation Time

Resources Average Power Consumption



$$E(res, i) = \int_{t0,i}^{S_{res}} P(t)\, dt \left[\frac{Joule}{Visit}\right] \quad (1)$$

$$ED(res) = \sum_{i=1}^{\#Visit} \int_{t0,i}^{S_{res,i}} P(t)\, dt [Joule] \quad (2)$$

$$E(res) = \frac{ED(res)}{\#Visit} \left[\frac{Joule}{Visit}\right] \quad (3)$$

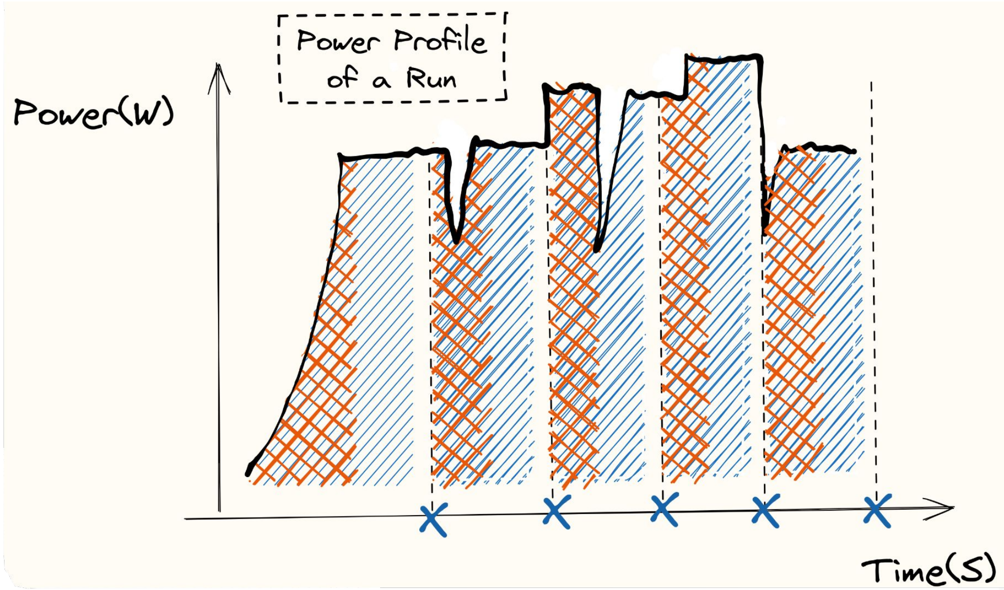
$$e(res) = \frac{E(res)}{S(res)} \left[\frac{Joule}{s}\right] \quad (4)$$

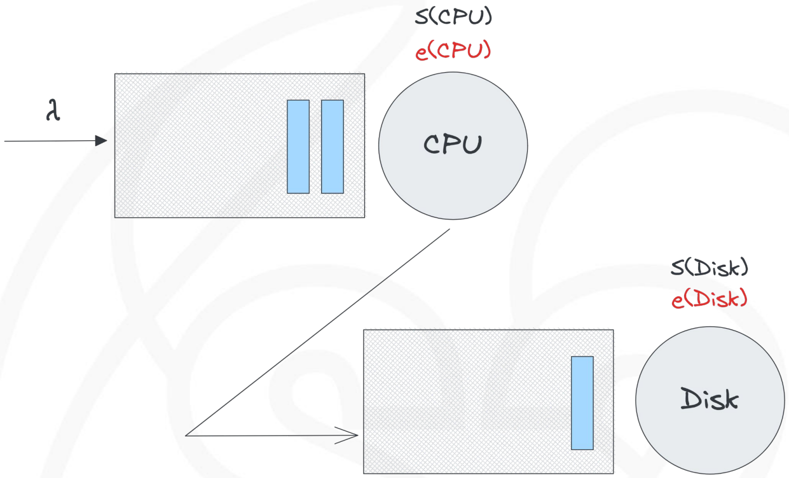
CPU-Time

Disk-Time

Observation Time

Resources Average Power Consumption





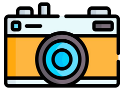
CPU-Time

Disk-Time

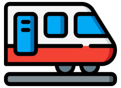
X Observation Time

Resources Average Power Consumption

Two Case Studies:



Digital Camera [3]



Train Ticket Booking System [4]

For each case:

1. Observe the system under **scaled** workloads
2. Create a Layered Queuing Network (LQN) parametrized with measures obtained in the **shortest** experiment
3. **Compare** estimates vs measurements

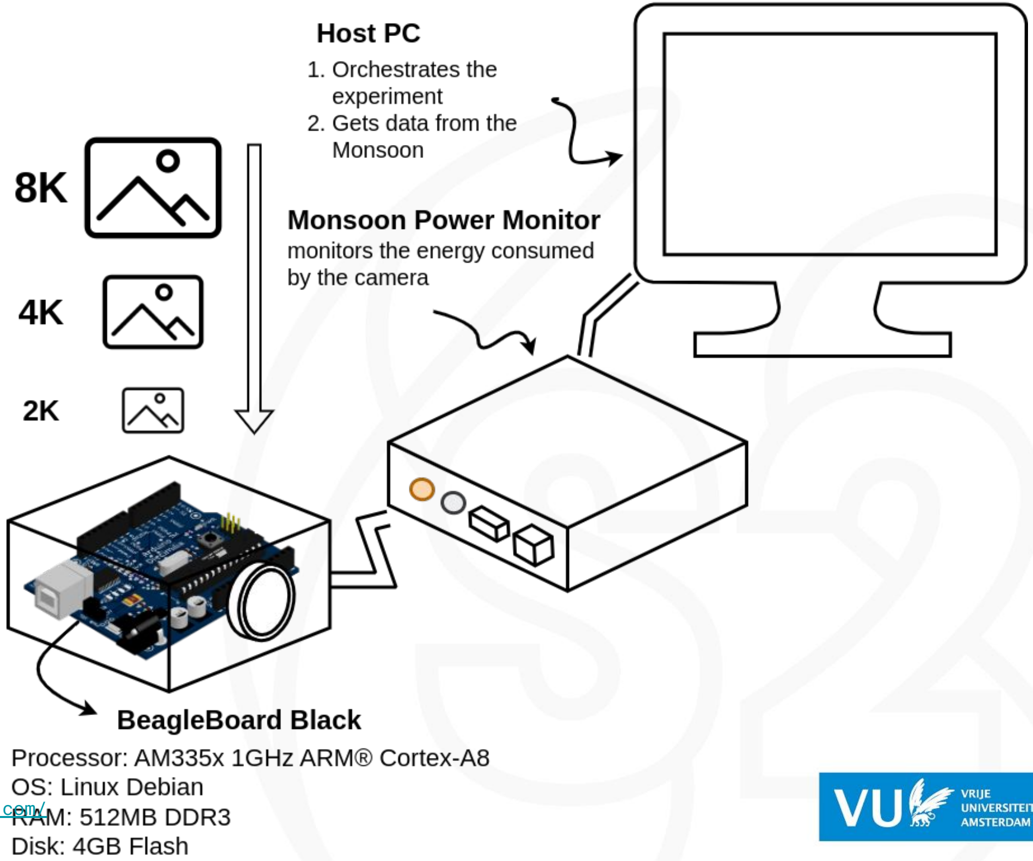
Our approach, at the moment, considers only the cases in which *energy consumption* ***grows linearly*** *with execution time*

F. Vahid and T. Givargis, *Embedded System Design: A Unified Hardware/Software Introduction*, John Wiley & Sons, Inc., USA, 1st edition, 2001
Fudan Software Engineering Laboratory, *Train Ticket Booking System*, https://github.com/FudanSELab/train-ticket, accessed: 2023-04-12

Digital Camera

A total of **thirty batches** are provided to the application, i.e., 10 per format.

A batch contains **30 pictures** of the same format chosen between 2K, 4K, and 8K



[5] Monsoon Solutions Inc, *Monsoon Power Monitor*, https://www.msoon.com/

Digital Camera

Format	Response Time (s)	CPU Utilization (%)	e (J/s)	Average Energy (J)
2K	60.30 - 60.30	96.30 - 96.48	**1.57**	95.27 - 95.16
4K	240.36 - **240.30**	96.76 - 96.12	1.59	382.46 - **379.24**
8K	960.73 - **960.60**	97.39 - 96.06	1.59	1537.96 - **1516.04**

Cells presenting two values have measured value, on the left, and estimate, on the right

$$e(res) = \frac{E(res)}{S(res)}[\frac{Joule}{s}] \Rightarrow E(res) = e(res) \times S(res)[Joule]$$

Train Ticket Booking System

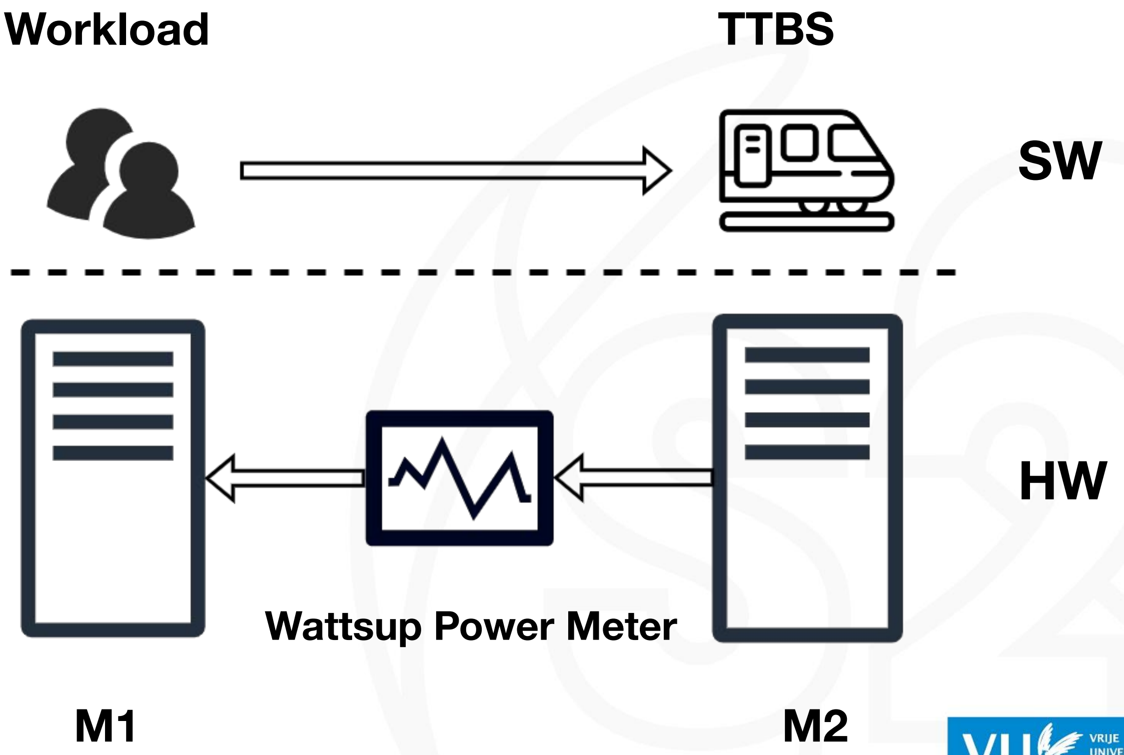
M2

Executes TTBS

M1

Generates **Bursts** of 75, 150, 225, 300, 375, 450, 500 Customers using **JMeter**

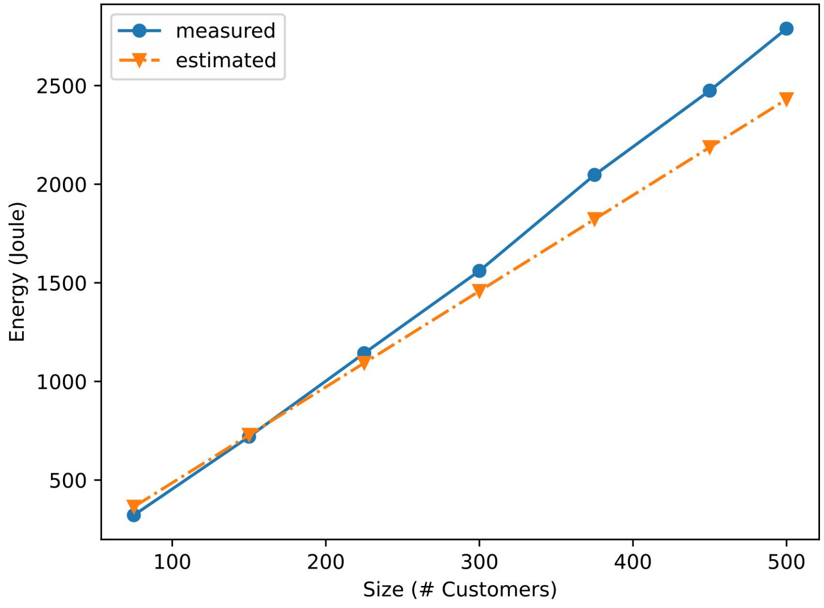
Records Performance and Power Consumption Values



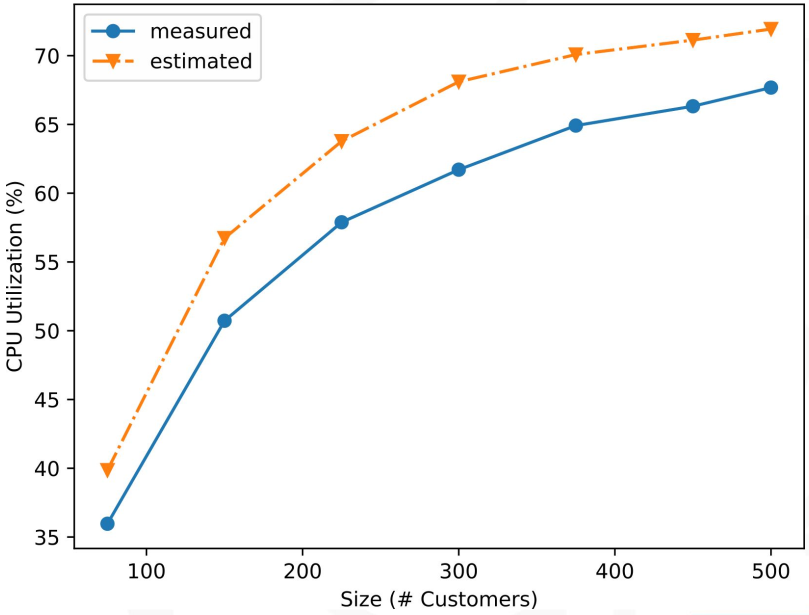
Power Meter Store, Watts Up Power Meter, https://www.powermeterstore.com/p1206/watts_up_pro.php

Train Ticket Booking System

Mean Absolute Percentage Error: (i) 9.24% **CPU Util.** (ii) 8.47% **Energy Consumption**
Experimentation Time: from 5 hours to 35 minutes



Energy Consumption



Performance

Thanks!
Any Questions?

email: v.stoico@vu.nl

IMG: Keith Haring, Untitled (Earth Day), 1985, https://emergencyartmuseum.com/haring