Energy-Efficient Mobile Web Computing

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The Web Evolution

1990

HTML

The Web Evolution

1990

HTML

The Web Evolution

1990

HTML

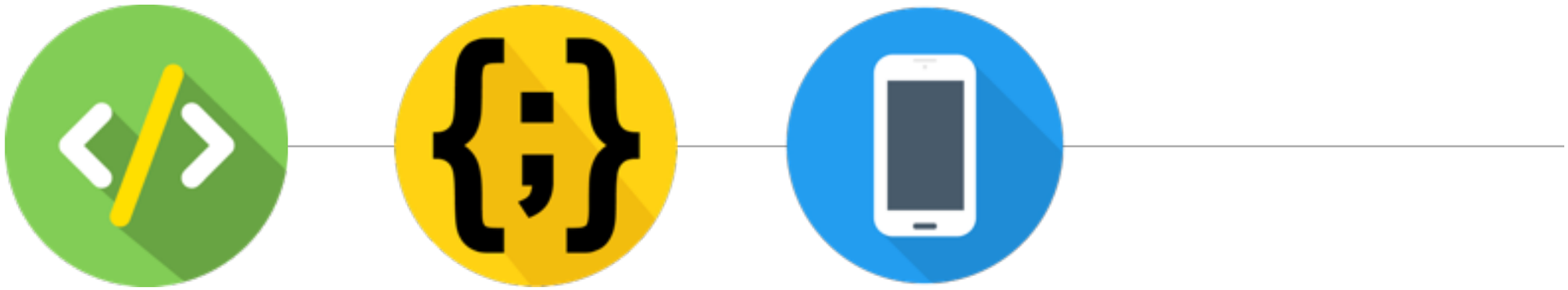
1996

JavaScript

The Web Evolution

1990
HTML

2008
Mobile Web



1996
JavaScript

The Web Evolution

1990
HTML

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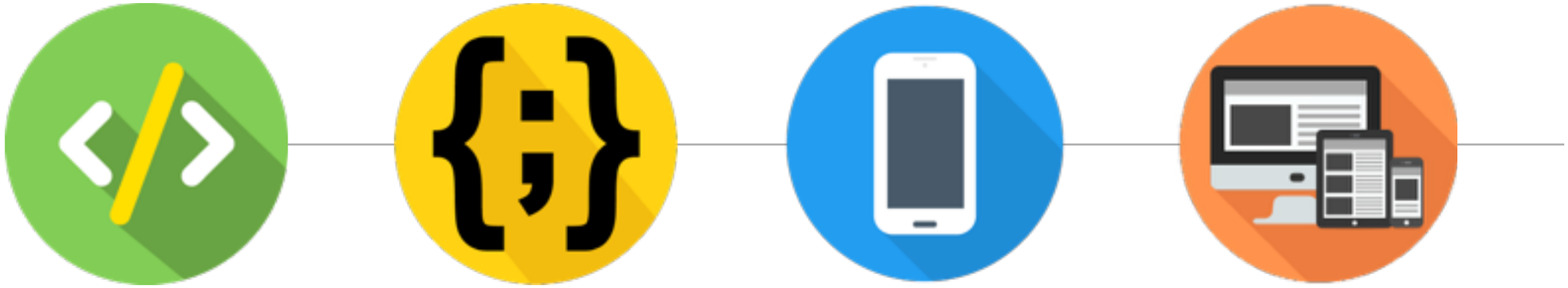
2008
Mobile Web

2012
Responsive Web

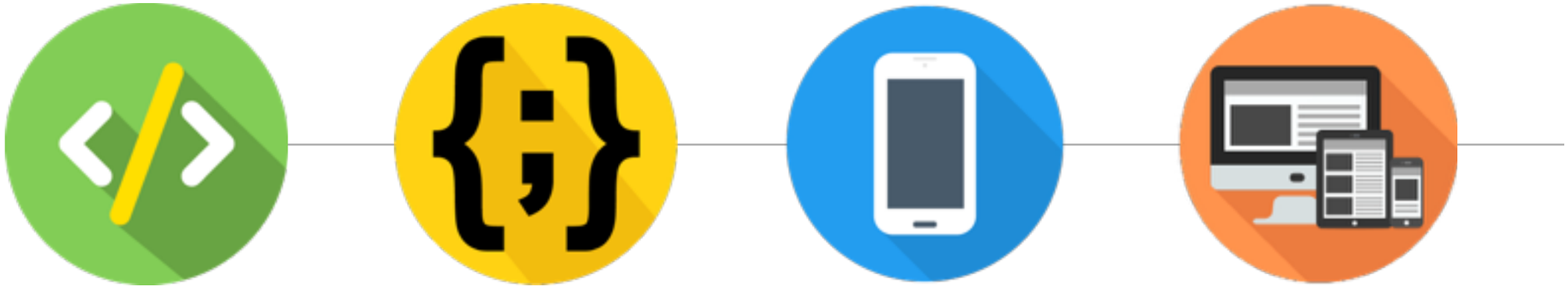


The Web Evolution

Functionality

1990
HTML

2008
Mobile Web



1996
JavaScript

2012
Responsive
Web

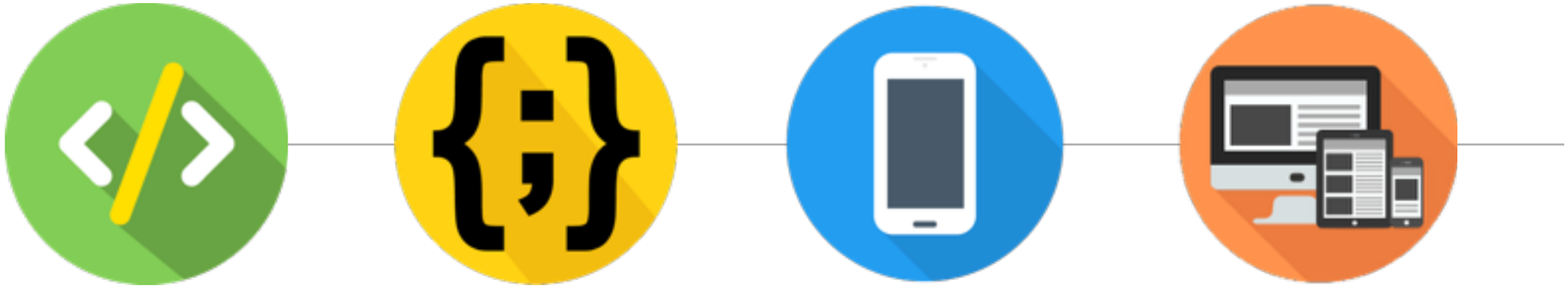
The Web Evolution

Functionality

Performance

1990
HTML

2008
Mobile Web



1996
JavaScript

2012
Responsive
Web

The Web Evolution

Functionality → Performance → Energy

1990
HTML

1996
JavaScript

2008
Mobile Web

2012
Responsive Web

2016
Watt Wise Web

The Web Evolution

Functionality

Performance

Energy

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HTML

1996
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Web: Mobile Overtaking Desktop

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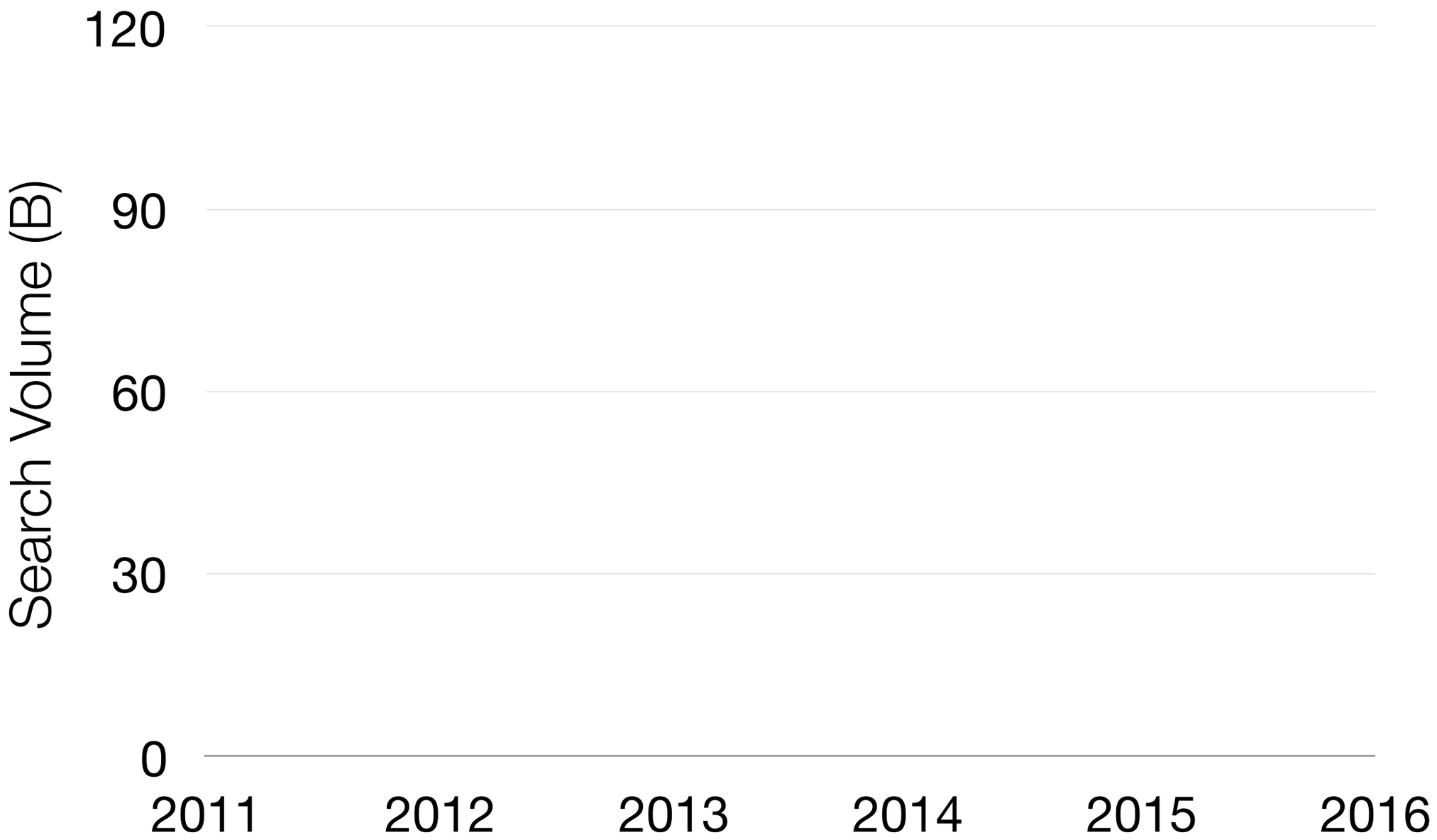
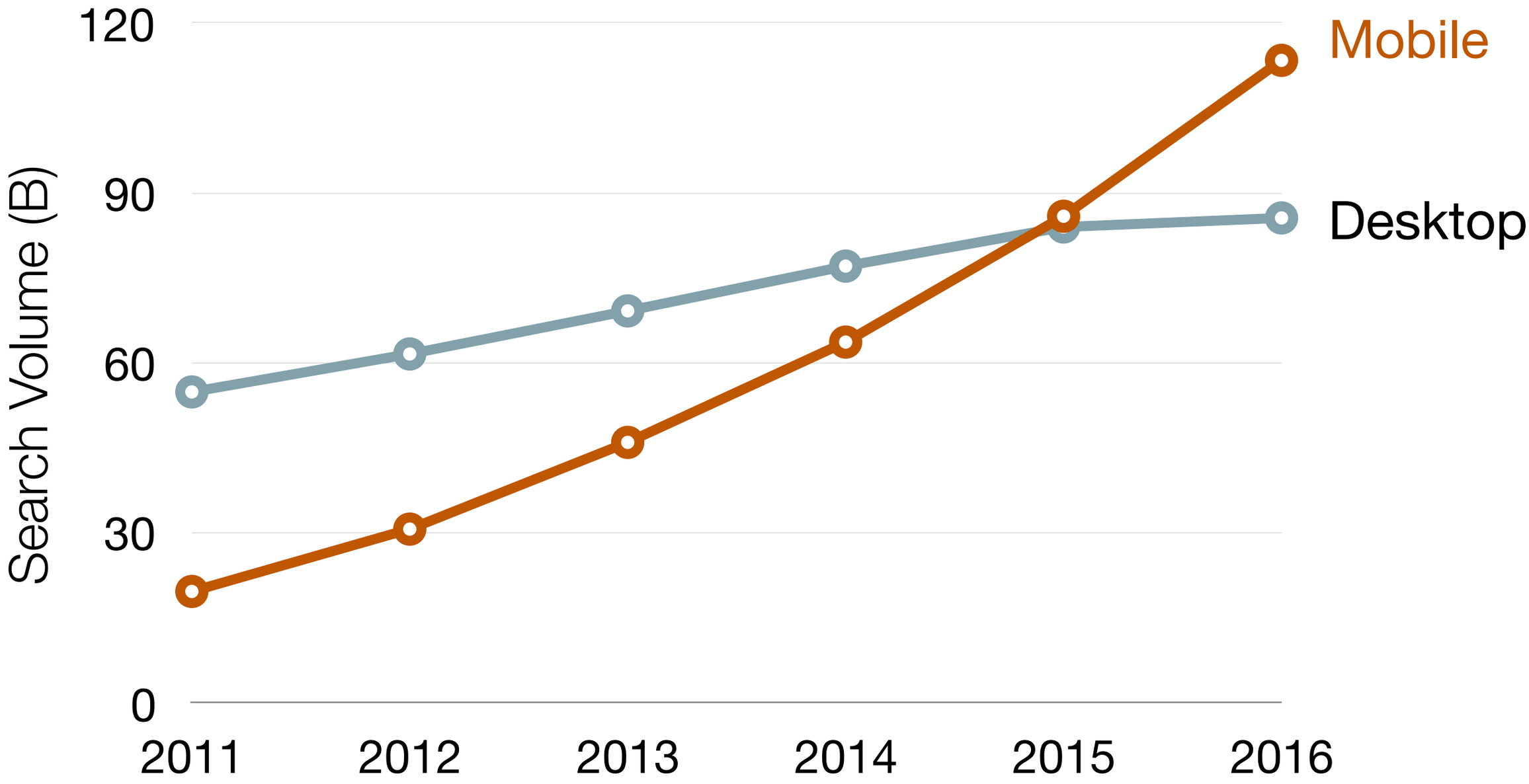


Source: BIA/Kelsey

Web: Mobile Overtaking Desktop



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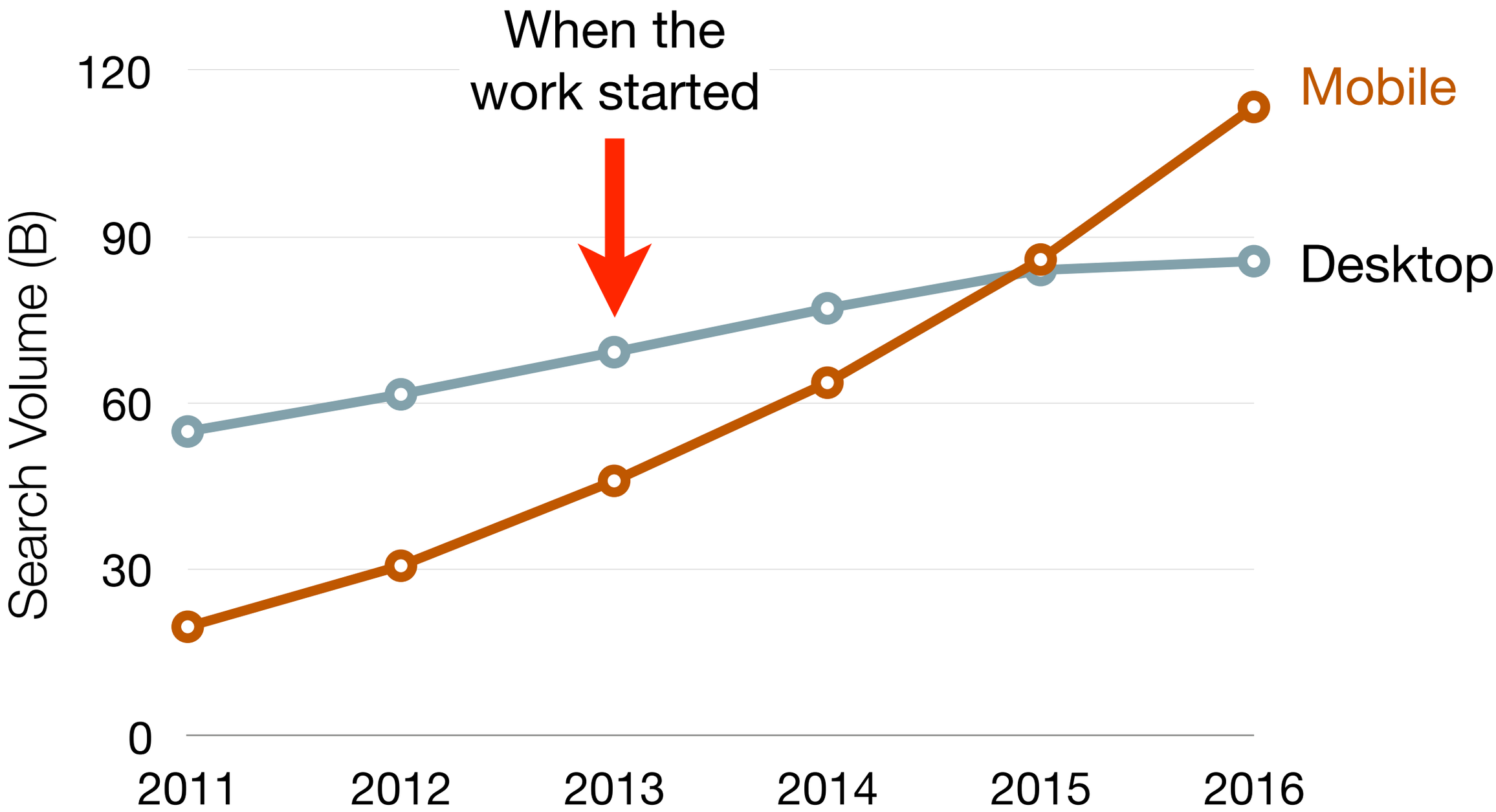

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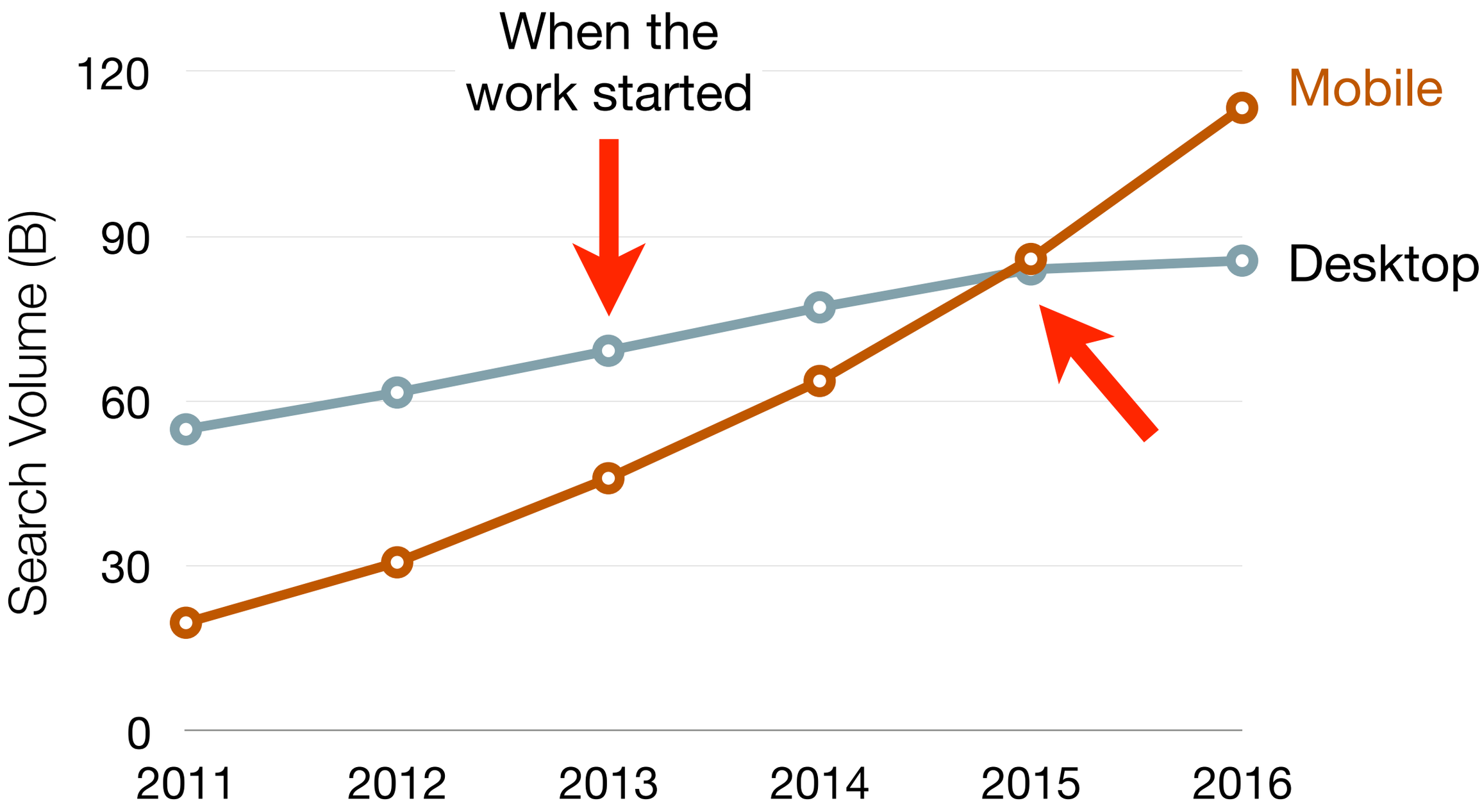
Web: Mobile Overtaking Desktop



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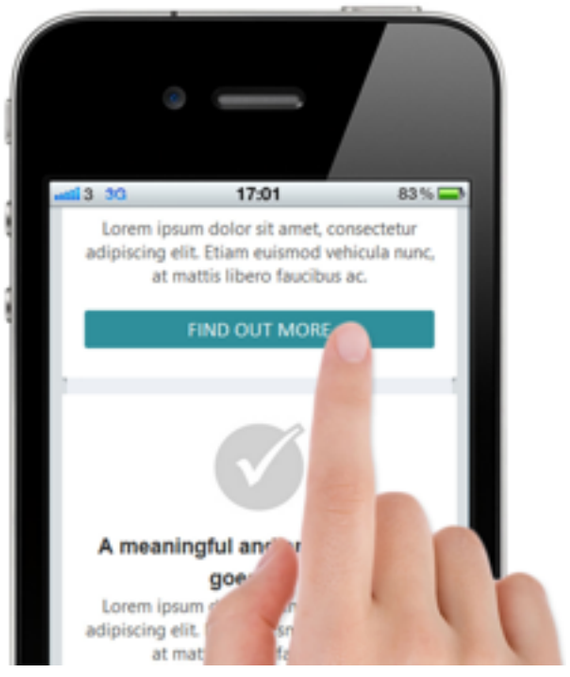
Web ≈ Mobile Web

The Scope of Mobile Web

Mobile
Client

The Scope of Mobile Web

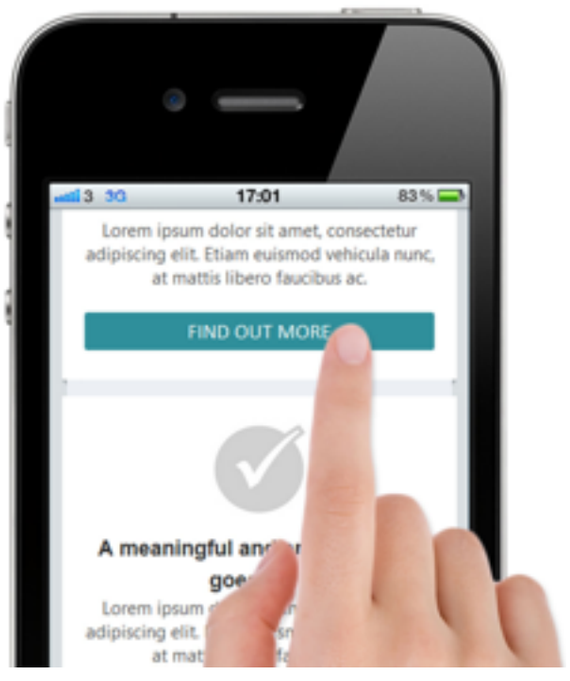
Mobile Client



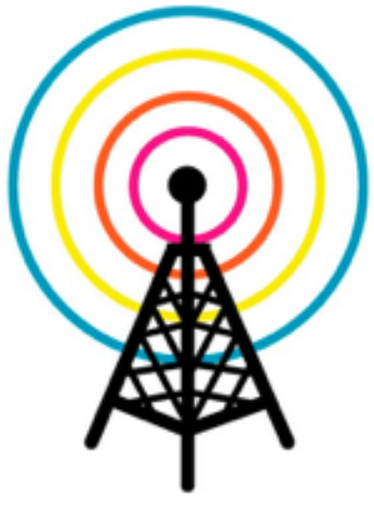
Cloud Web Servers

The Scope of Mobile Web

Mobile Client



Cellular Network



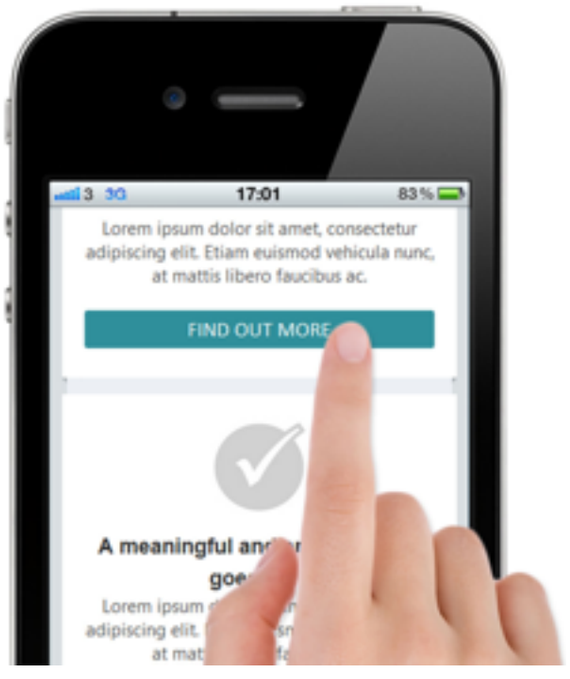
Cloud Web Servers

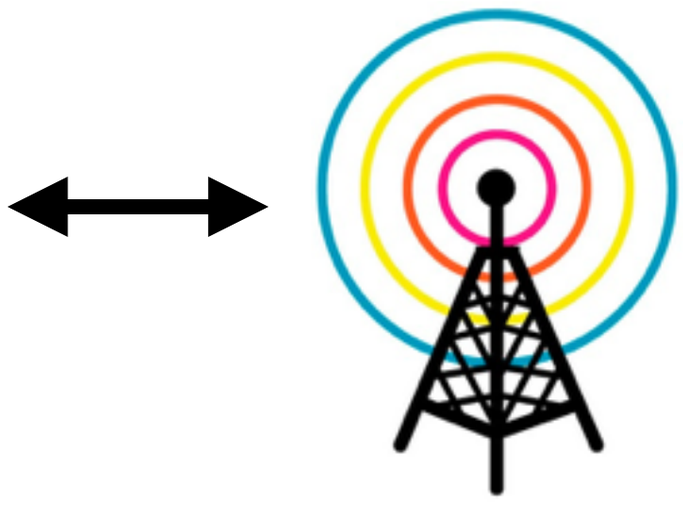
The Scope of Mobile Web

Mobile Client

Cellular Network

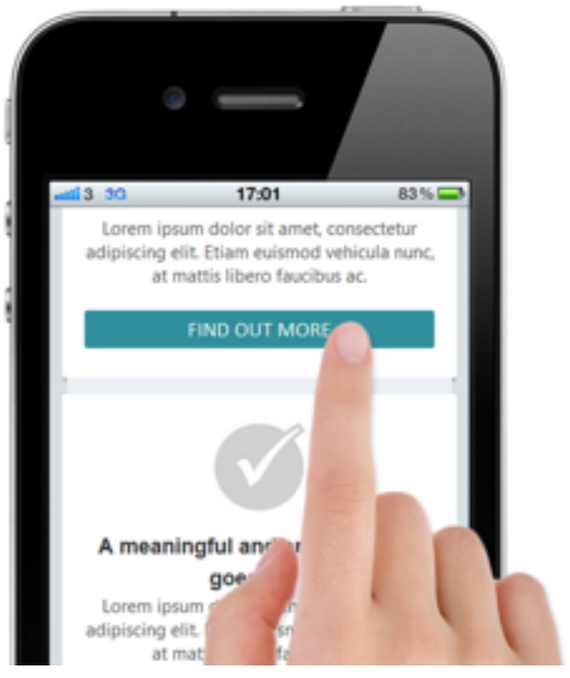
Cloud Web Servers





The Scope of Mobile Web

Mobile Client



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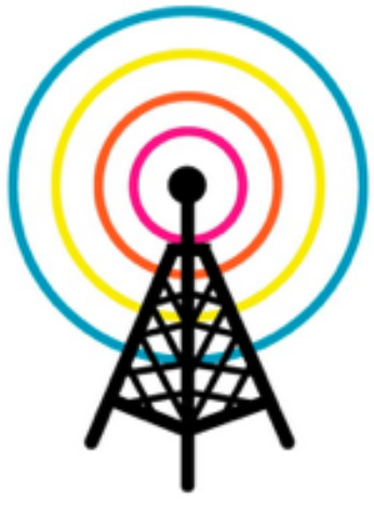


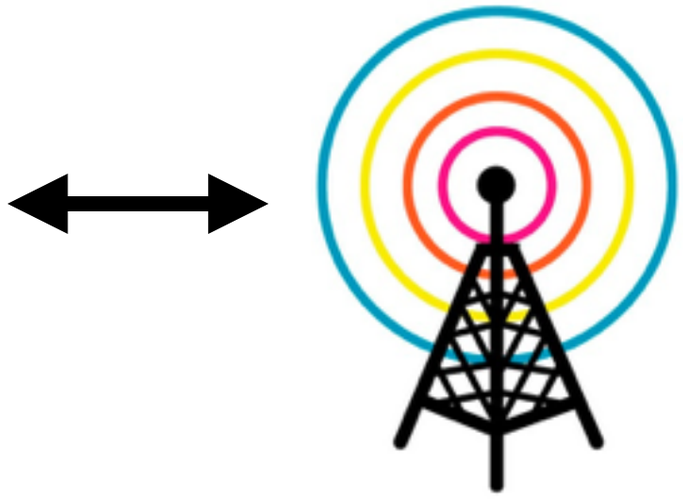
Cloud Web Servers

[MICRO 2015] (Top Picks Honorable Mention)

The Scope of Mobile Web

Mobile Client

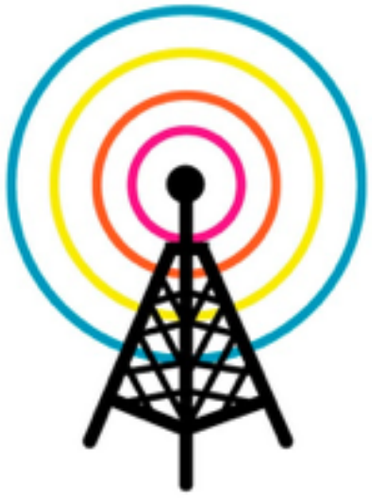
Cellular Network



The Scope of Mobile Web

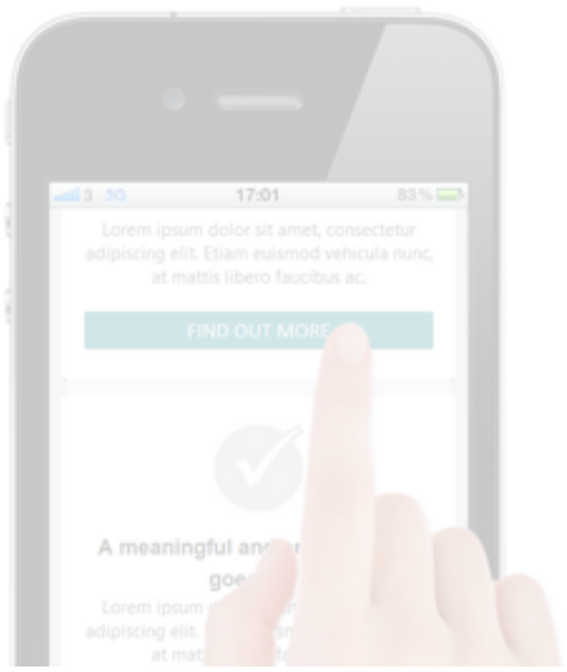
Mobile Client

Cellular Network



Isn’t Mobile Web a Network Issue?

Mobile Client



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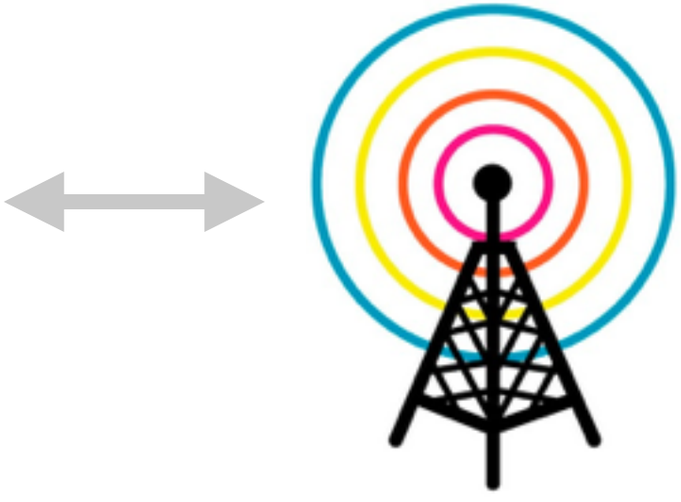

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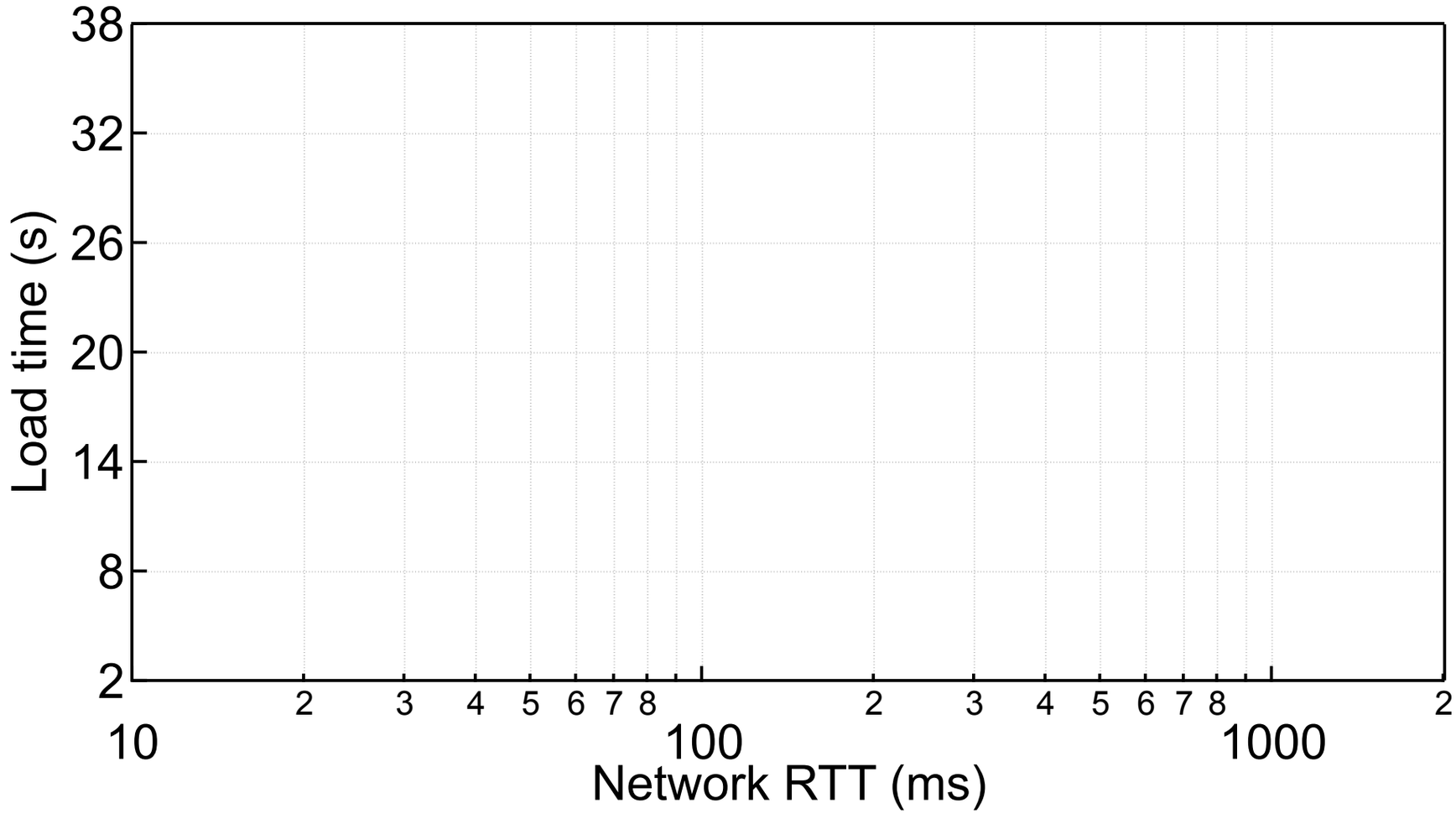
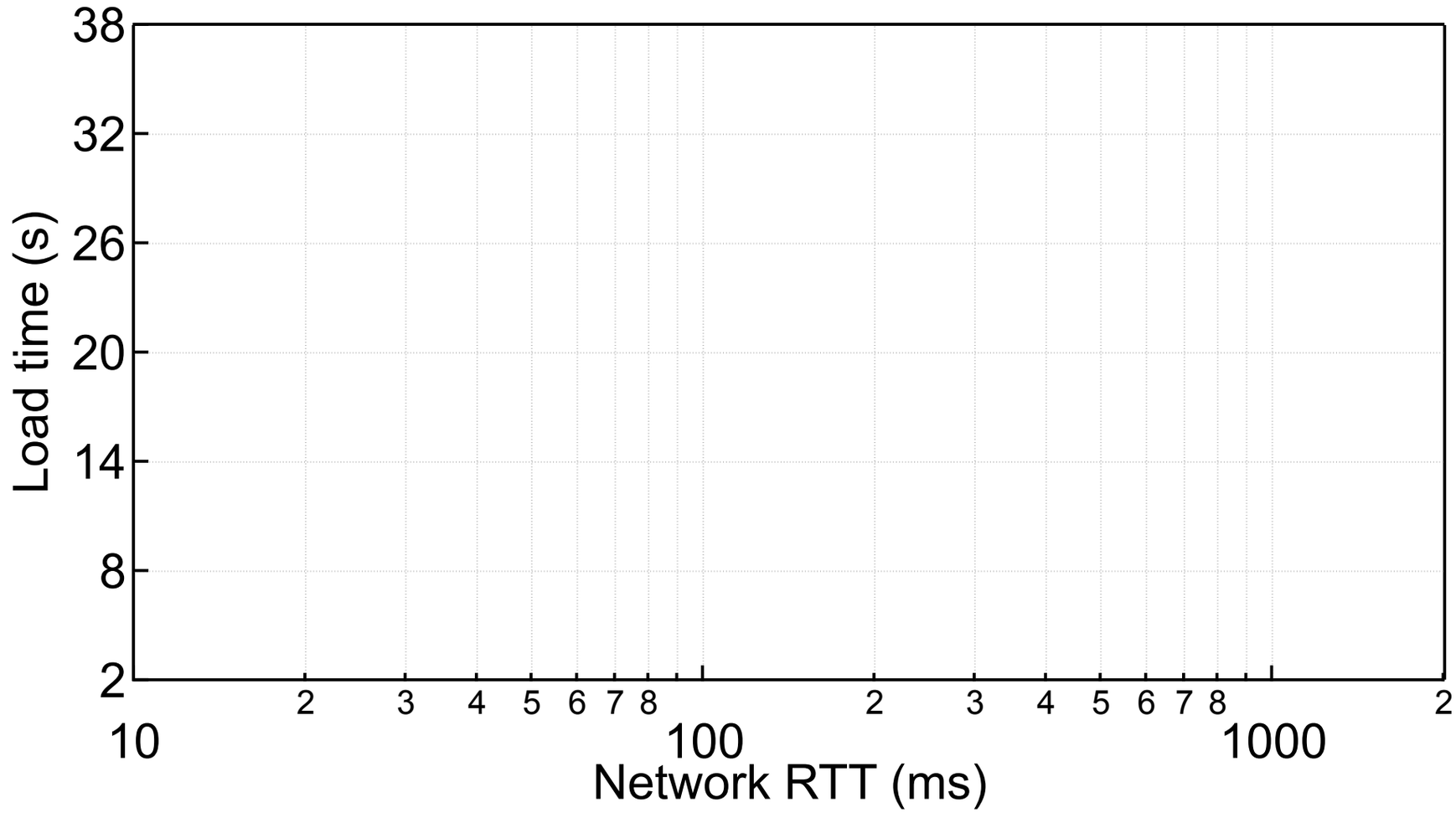


Isn’t Mobile Web a Network Issue?

- Samsung Galaxy S4 smartphone.
- Hot webpages from Alexa[1].
- Time measured using Navigation Timing API[2].



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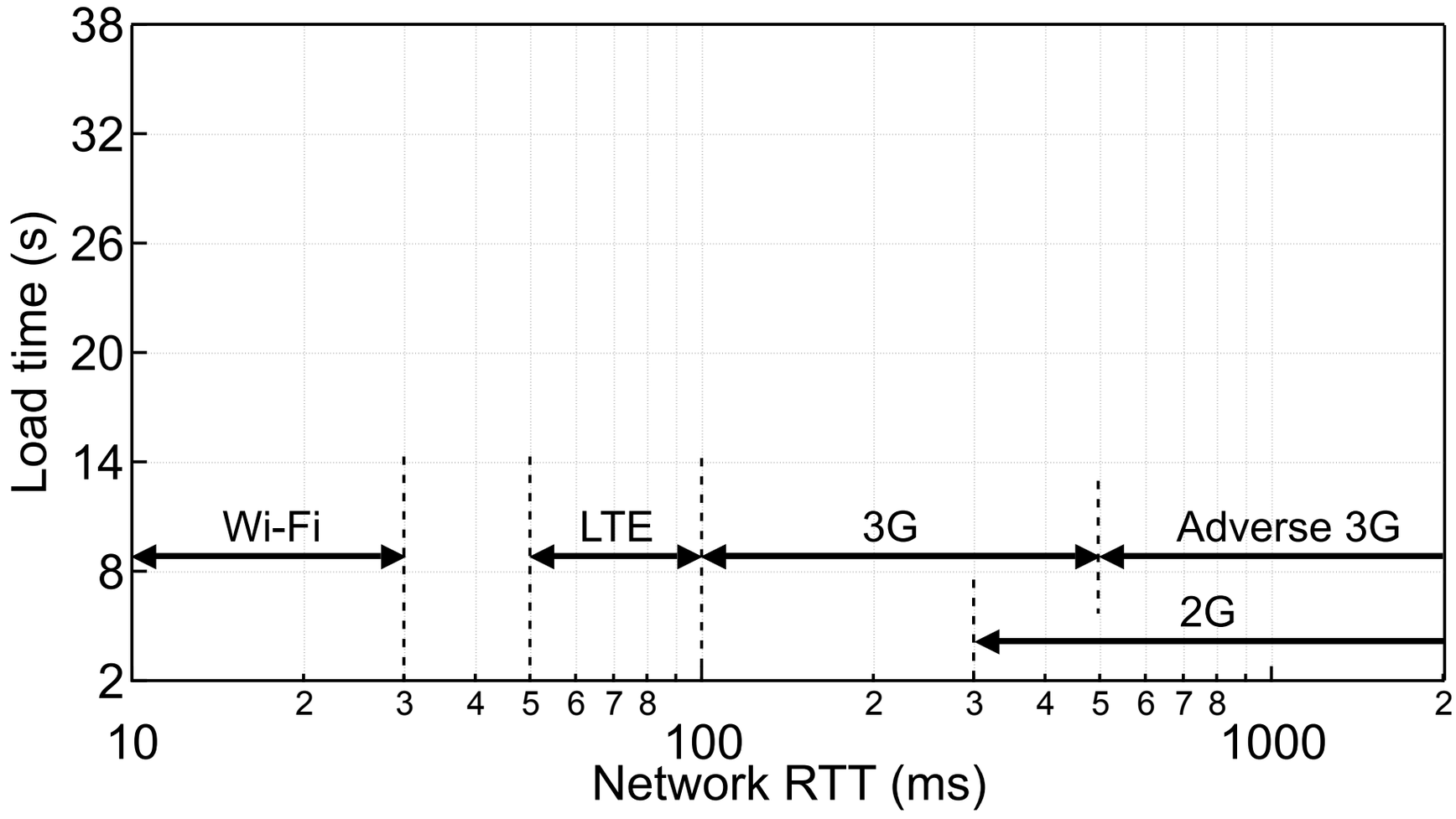

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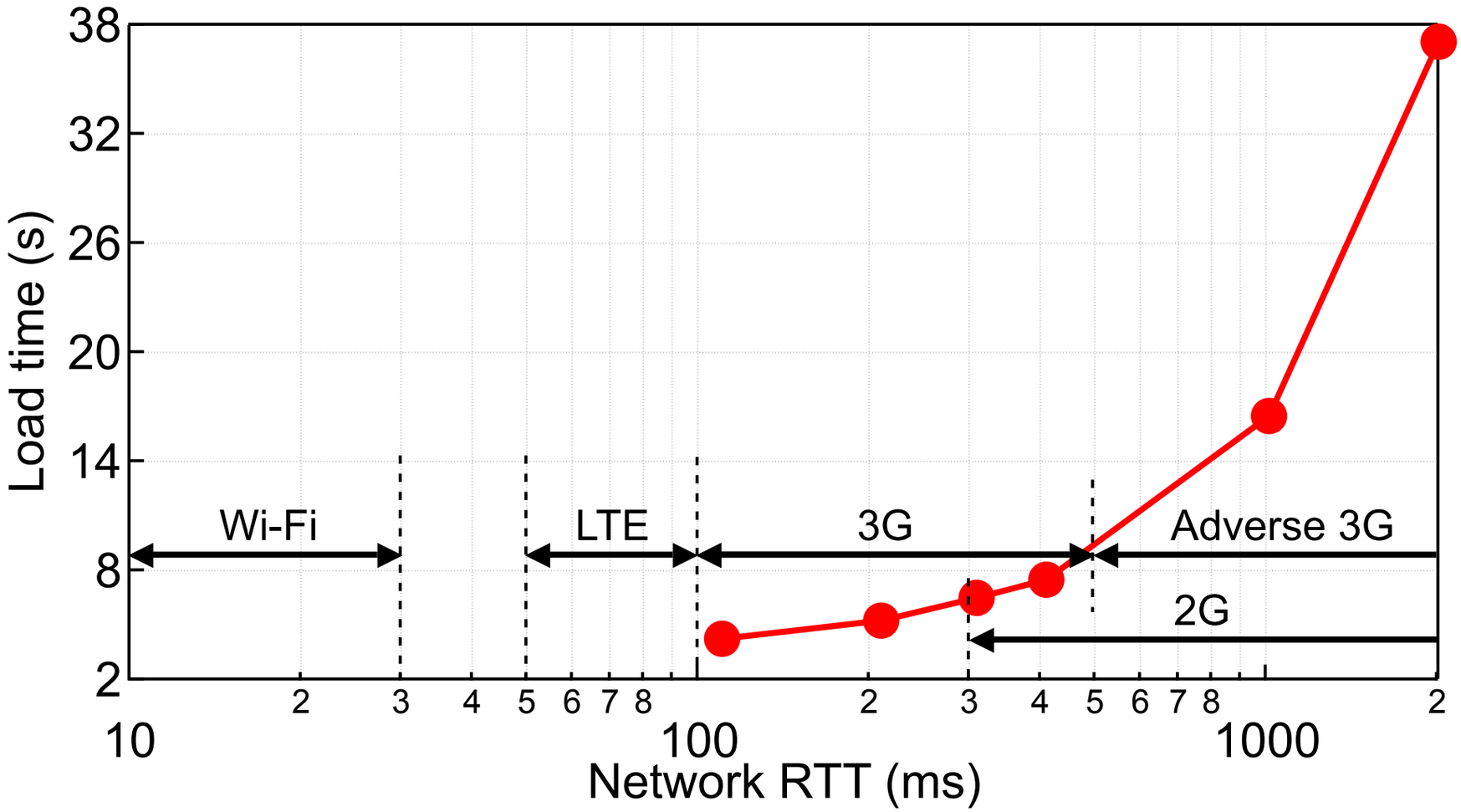

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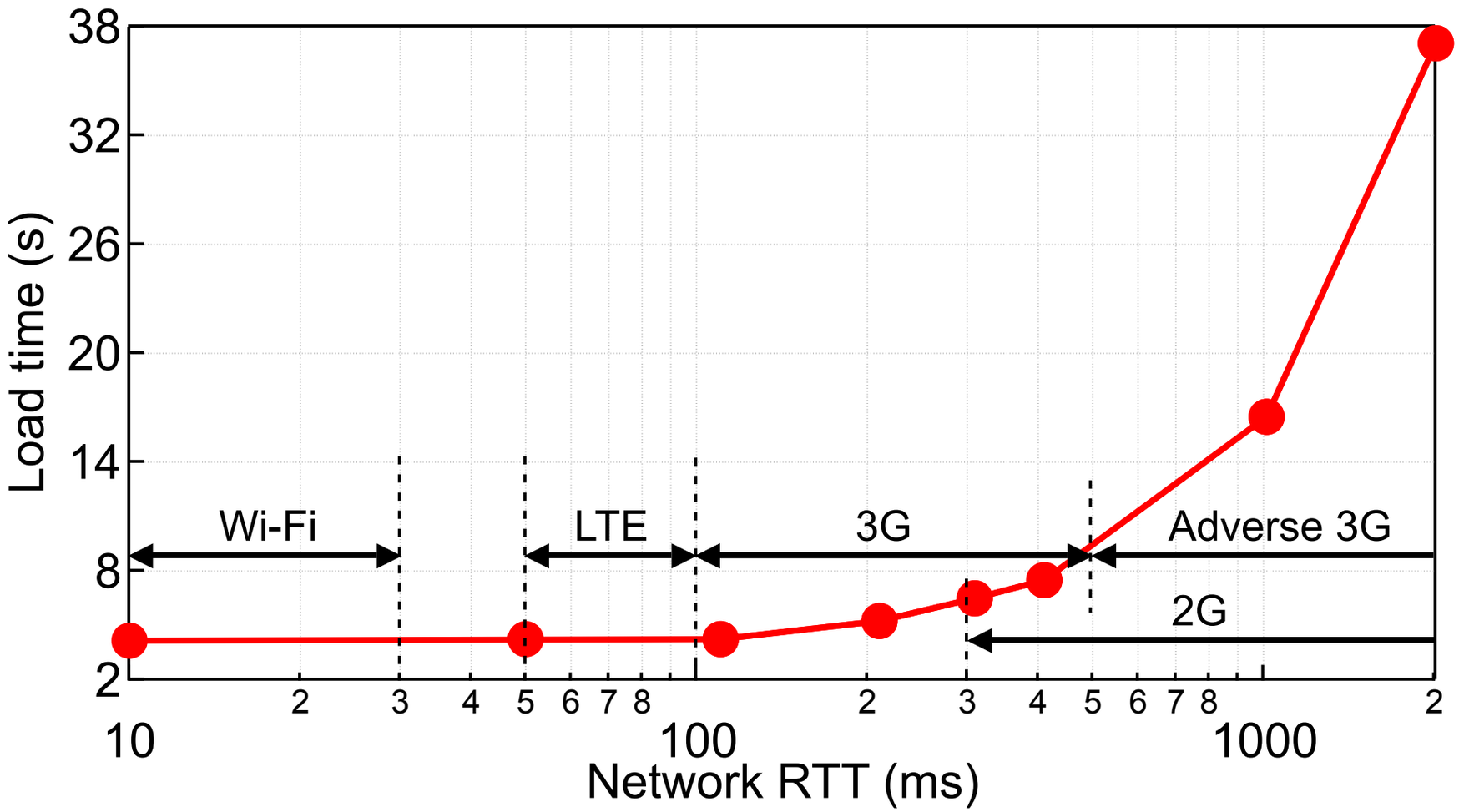

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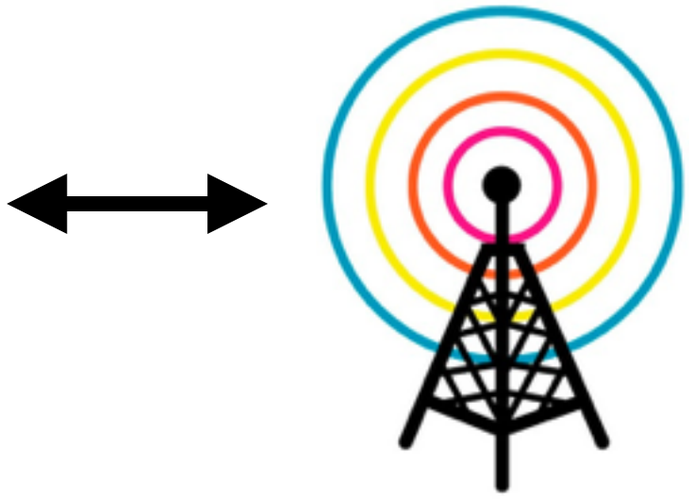
Mobile Web is also a Compute Issue!

Mobile Client

Cellular Network



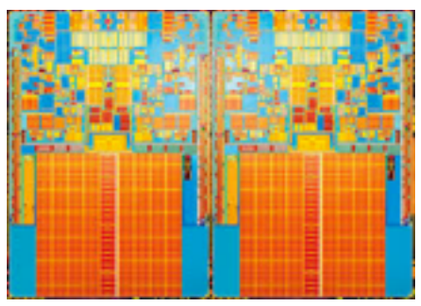
Mobile Web is also a Compute Issue!

Mobile Client

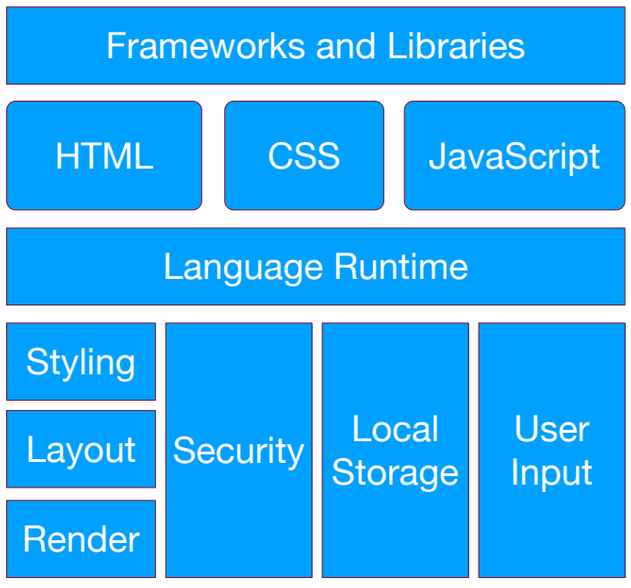
Cellular Network

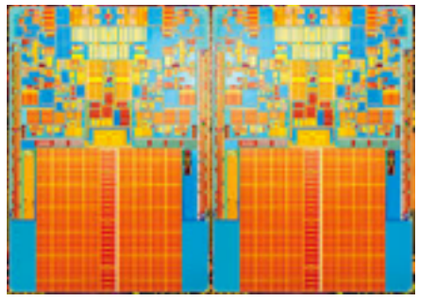
My Work

Traditional Approach

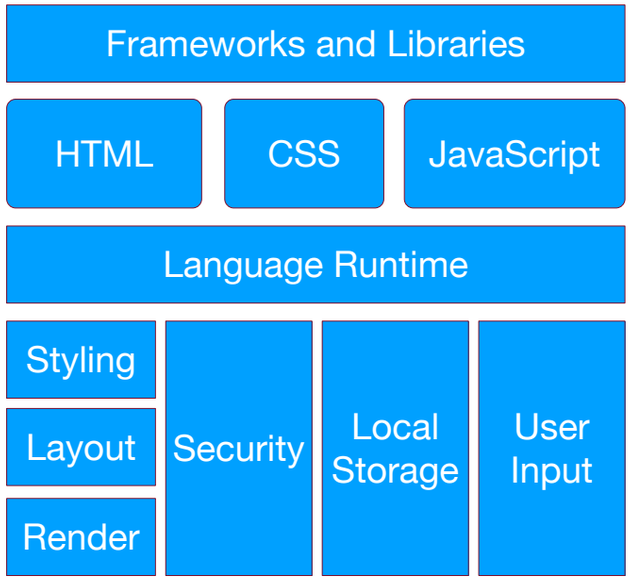


Traditional Approach

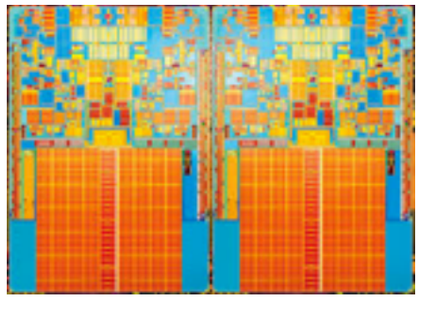




Traditional Approach



Application



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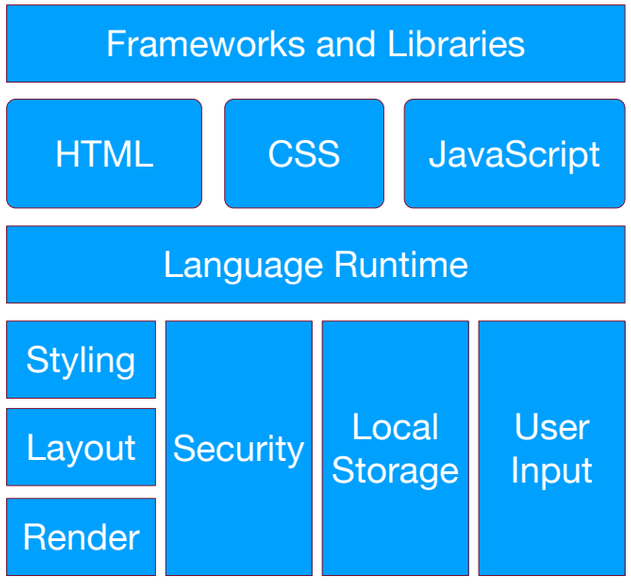
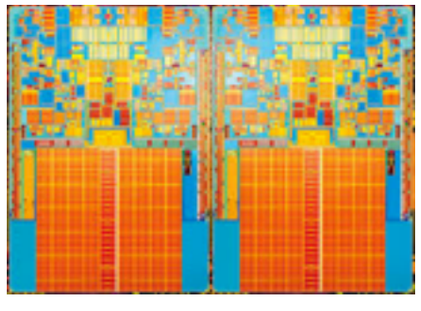
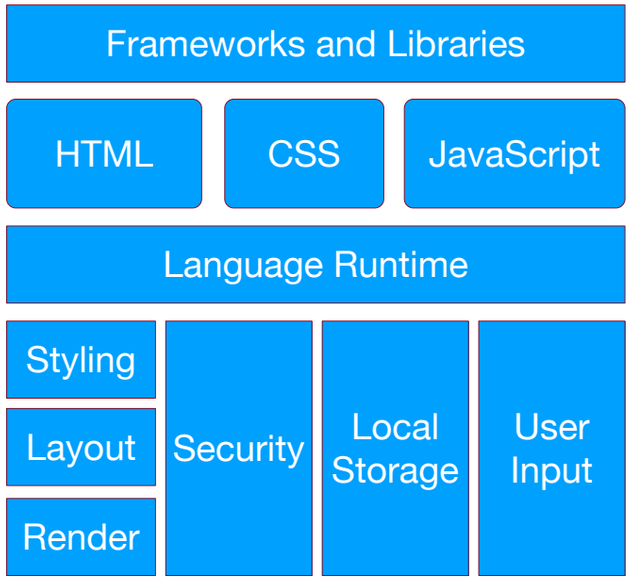


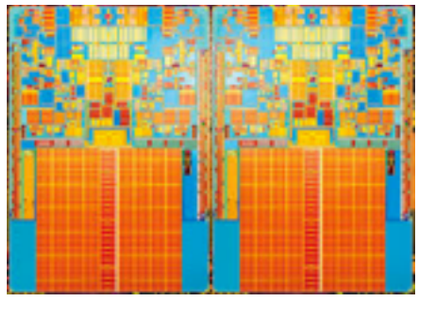


Application

- Parallelize browser computation

Traditional Approach



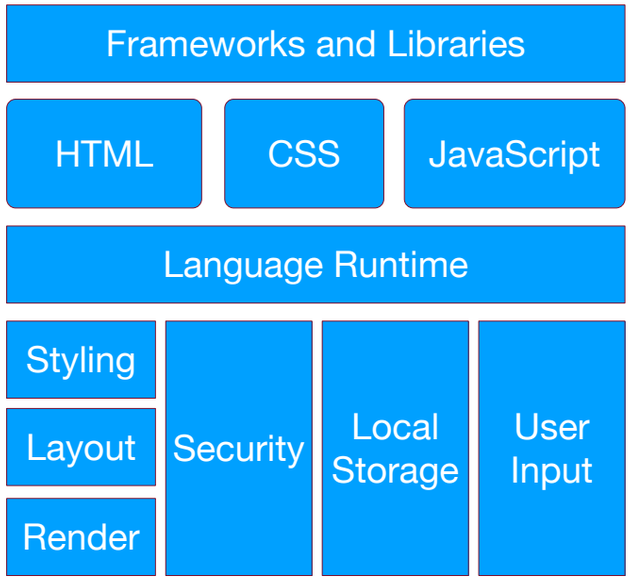


Application

- Parallelize browser computation

Architecture

Traditional Approach



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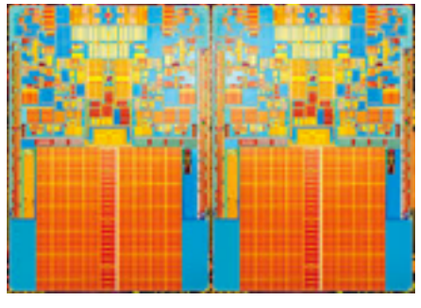
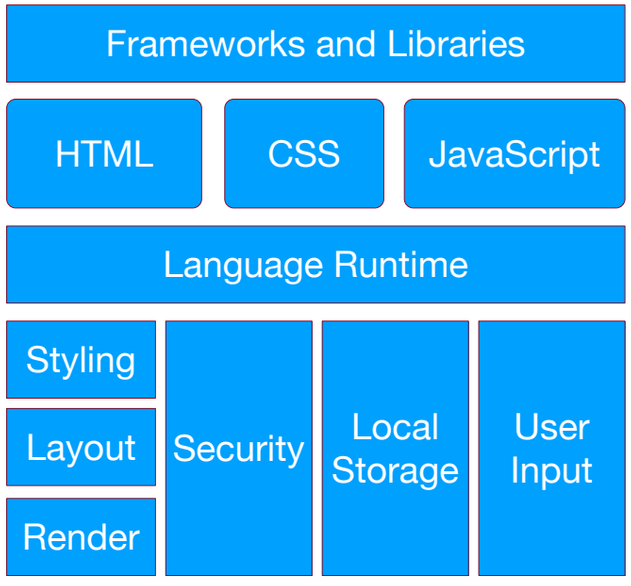


Architecture

- Voltage/frequency scaling on general-purpose processors

Traditional Approach

Inputs



Application

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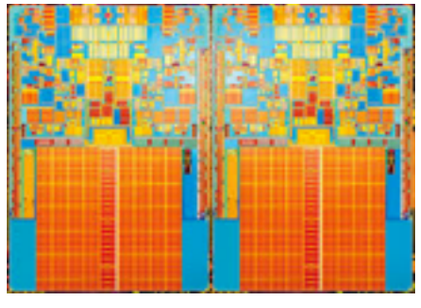


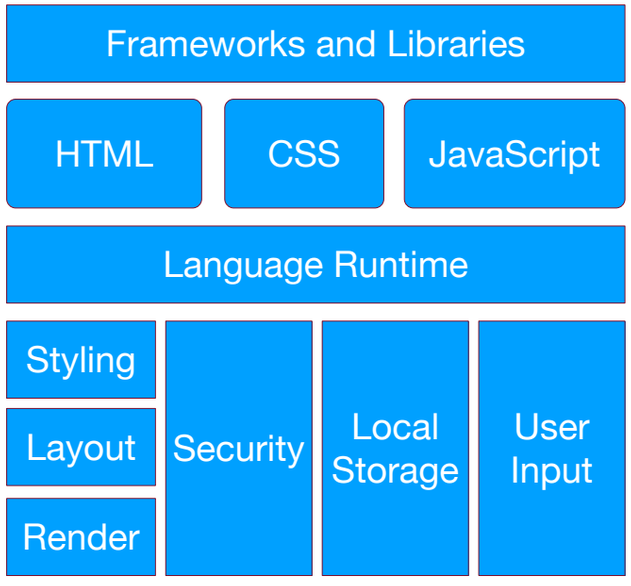
Architecture

- Voltage/frequency scaling on general-purpose processors

Traditional Approach

Inputs

- Ignored!



Application

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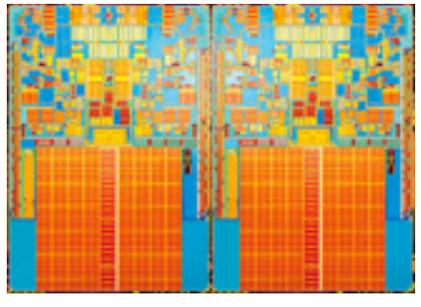

Architecture

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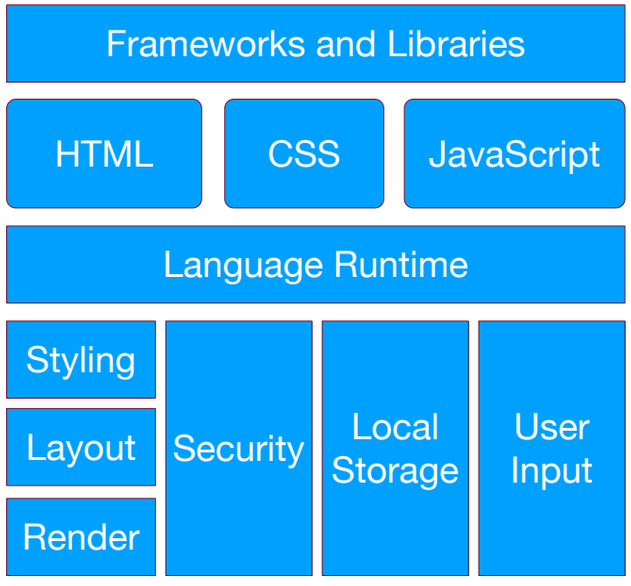

Application

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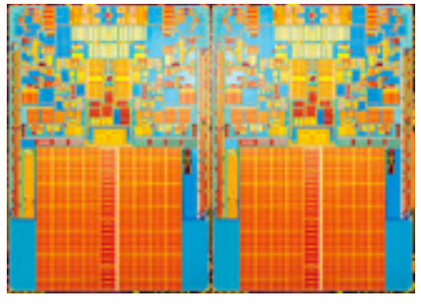


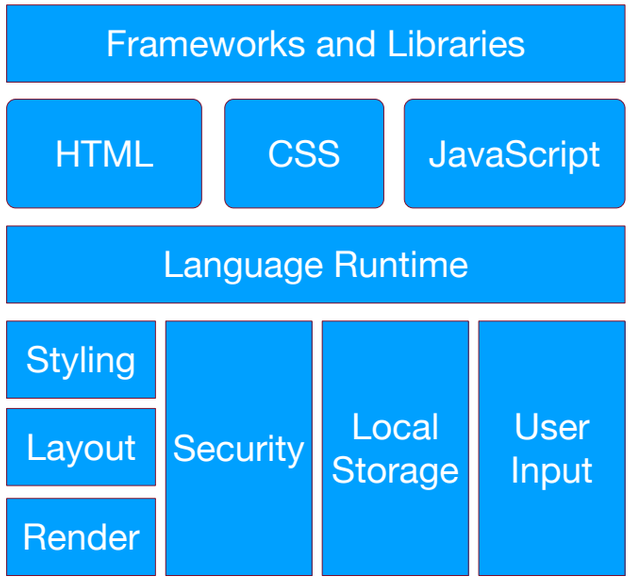
Architecture

- End of Dennard Scaling!
- Diminishing return

My Approach

Inputs

- Ignored!



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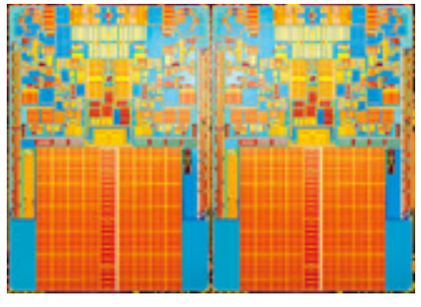
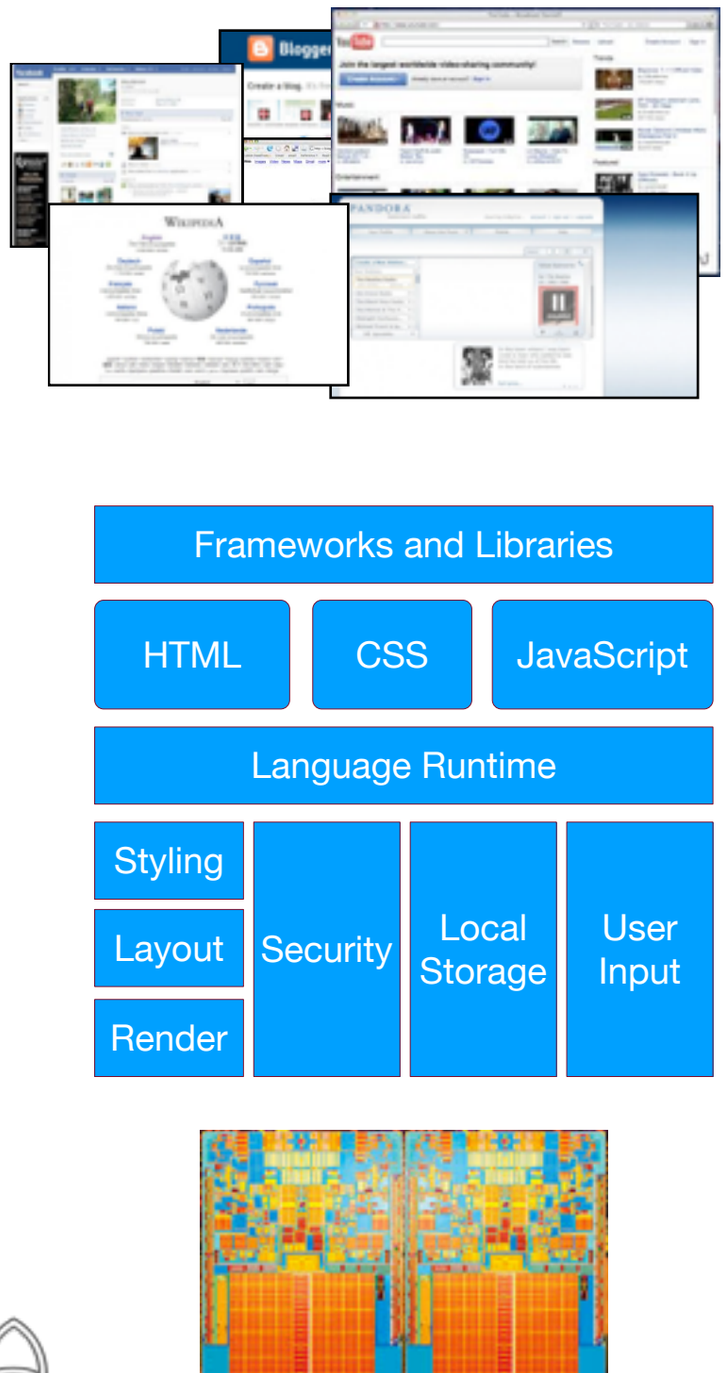


Architecture

WebCore

Web-specific Architecture

My Approach



Inputs

- Lost page-level diversity
- Lost user QoS requirements

Application

- Parallelize browser computation

Architecture

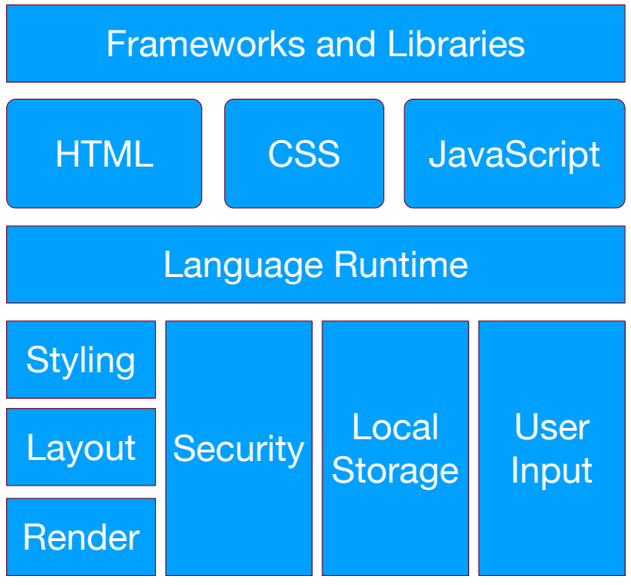
WebCore

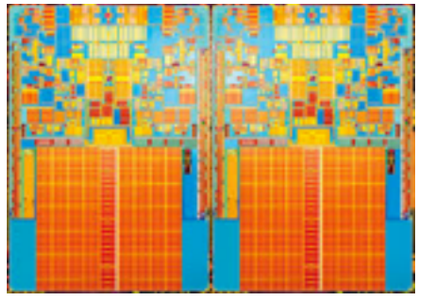
Web-specific Architecture

My Approach

Application

- Lost page-level diversity
- Lost user QoS requirements





Architecture

- Parallelize browser computation

WebCore

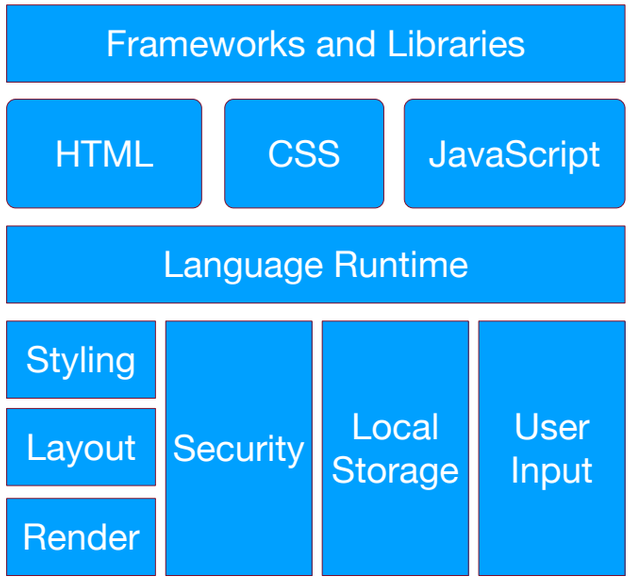
Web-specific Architecture

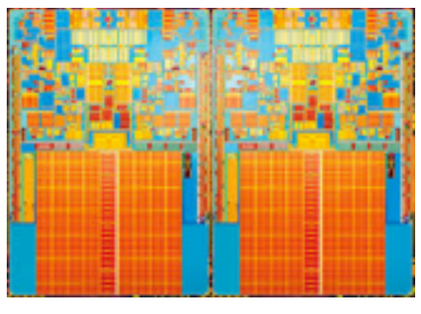
My Approach

Application

GreenWeb

Language Extensions





Architecture

WebCore

Web-specific Architecture

My Approach

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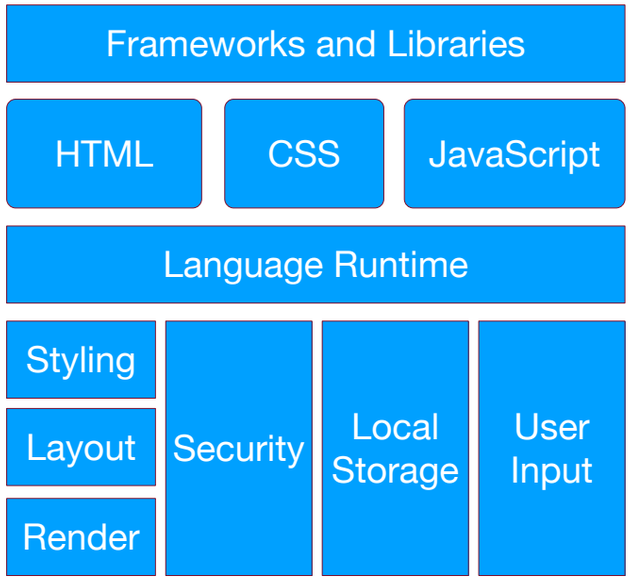
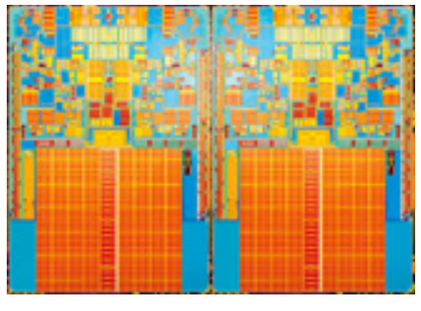


Runtime



Architecture

WebCore

Web-specific Architecture

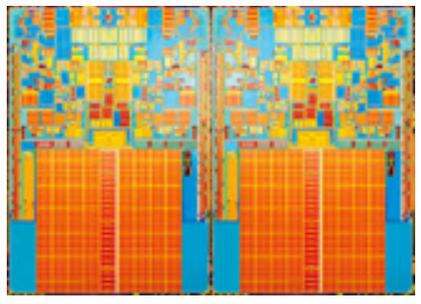
My Approach

Frameworks and Libraries

HTML | CSS | JavaScript

Language Runtime

Styling | Layout | Render | Security | Local Storage | User Input



Application

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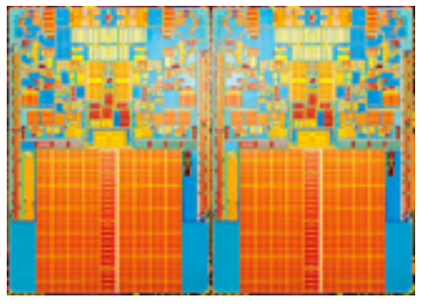

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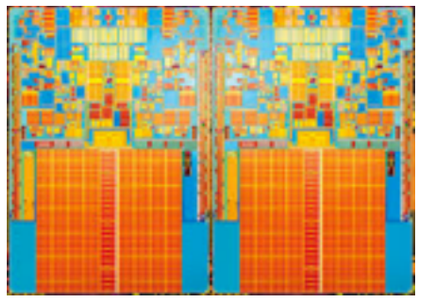


Application

Runtime

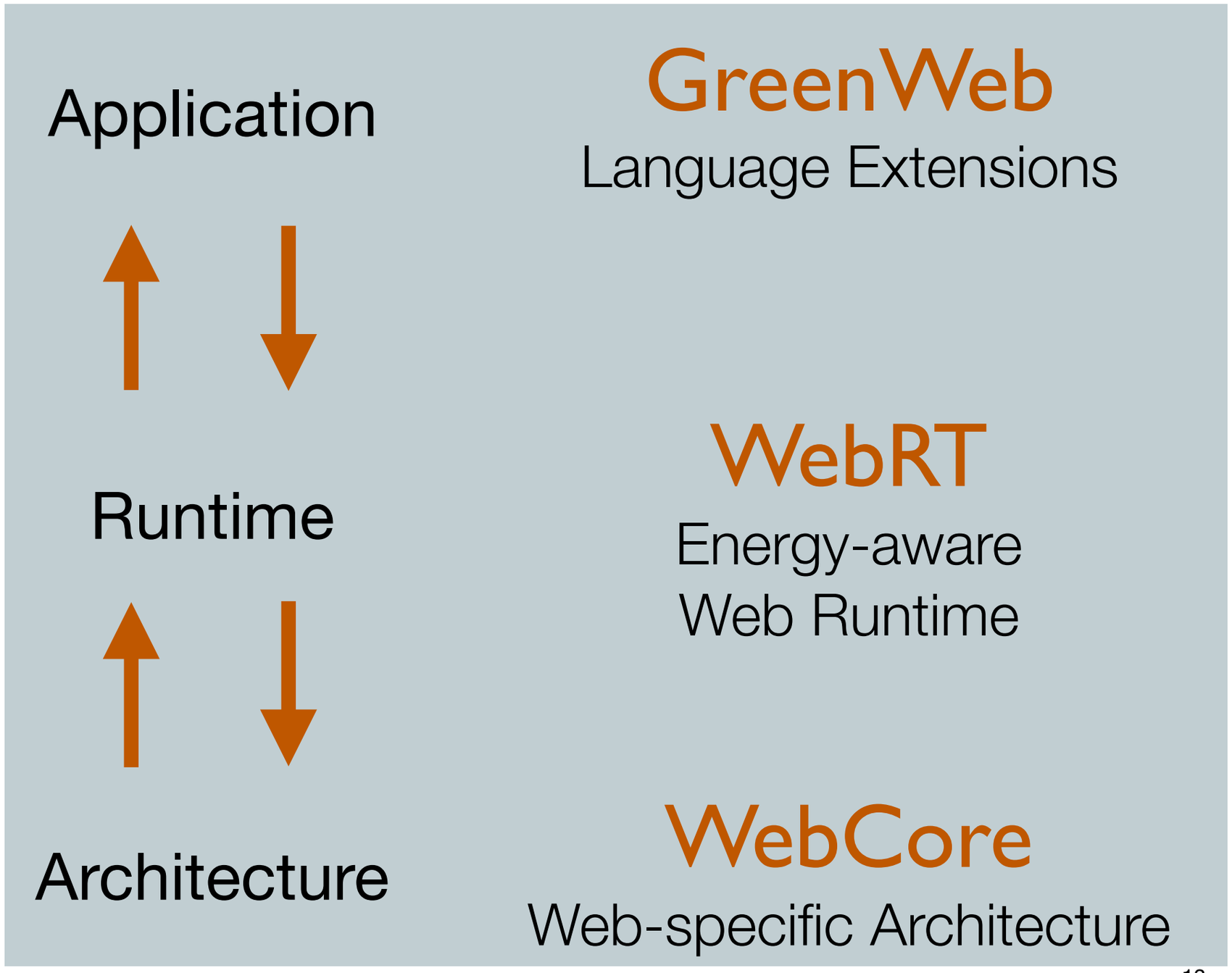
Architecture

GreenWeb
Language Extensions

WebRT
Energy-aware
Web Runtime

WebCore
Web-specific Architecture

My Approach


Application
GreenWeb
Language Extensions
Runtime
WebRT
Energy-aware
Web Runtime
Architecture
WebCore
Web-specific Architecture

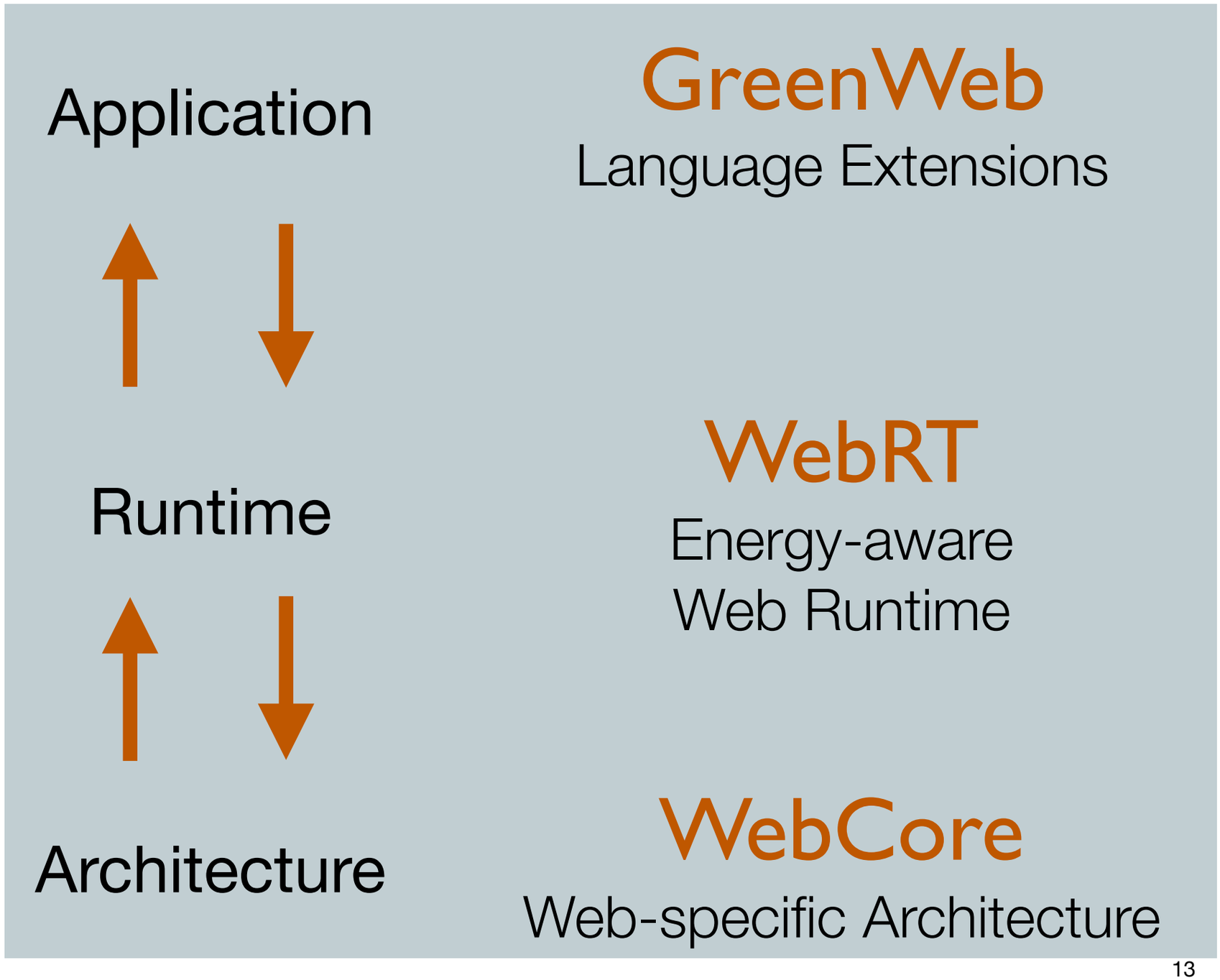
My Approach

My Dissertation Work

[PLDI 2016]

[HPCA 2013]
[HPCA 2015]
[CAL 2014]
(Best of CAL)

[ISCA 2014]



Thesis Statement

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Future mobile Web systems can achieve energy-efficiency without sacrificing responsiveness by incorporating:

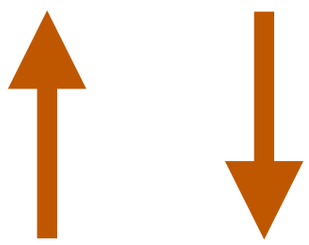
Thesis Statement

Future mobile Web systems can achieve energy-efficiency without sacrificing responsiveness by incorporating:

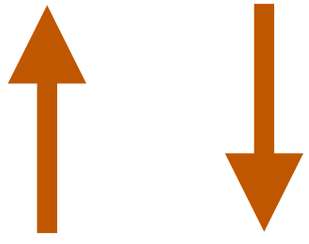
- Programming language annotations to convey user QoS information
- Runtime scheduling mechanisms to exploit heterogeneous hardware
- Hardware accelerators specialized for the key computation kernel

My Approach

Application



Runtime



Architecture

GreenWeb
Language Extensions

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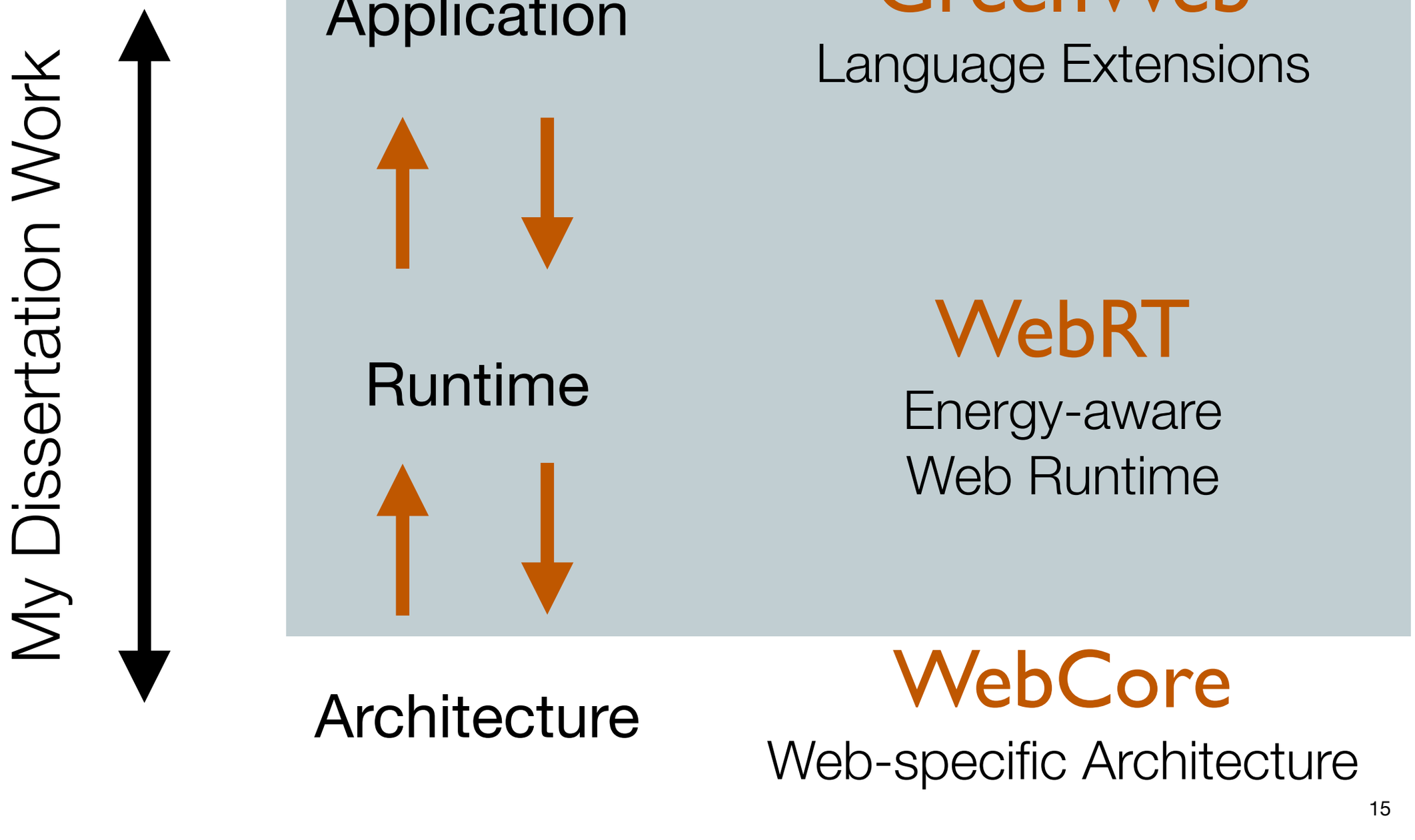
My Approach


My Dissertation Work
Application
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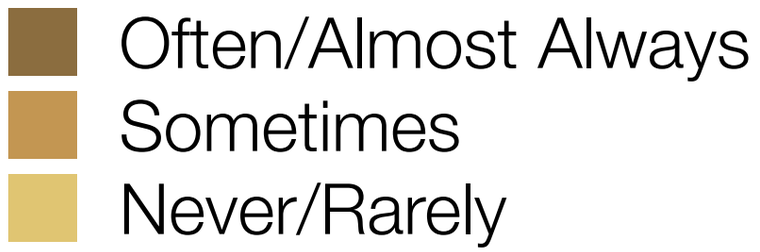
Energy Concern Among Mobile Developers

[ICSE 2016] Manotas et al., “An Empirical Study of Practitioners’ Perspectives on Green Software Engineering”

Energy Concern Among Mobile Developers

"My applications have requirements about energy usage."



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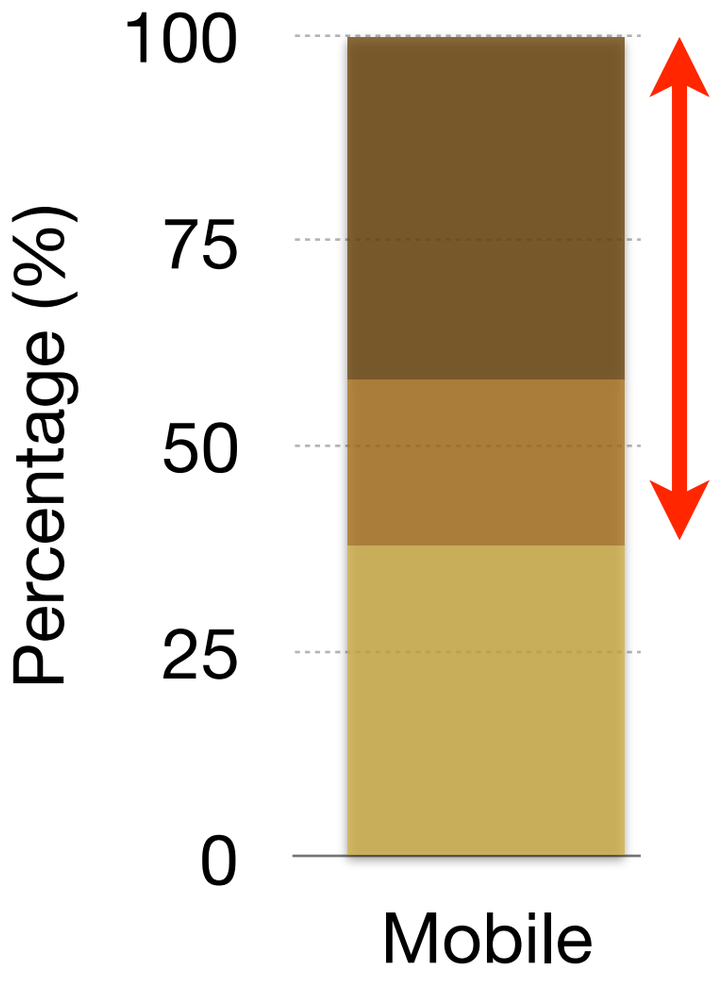
Energy Concern Among Mobile Developers



"My applications have requirements about energy usage."

- Often/Almost Always
- Sometimes
- Never/Rarely

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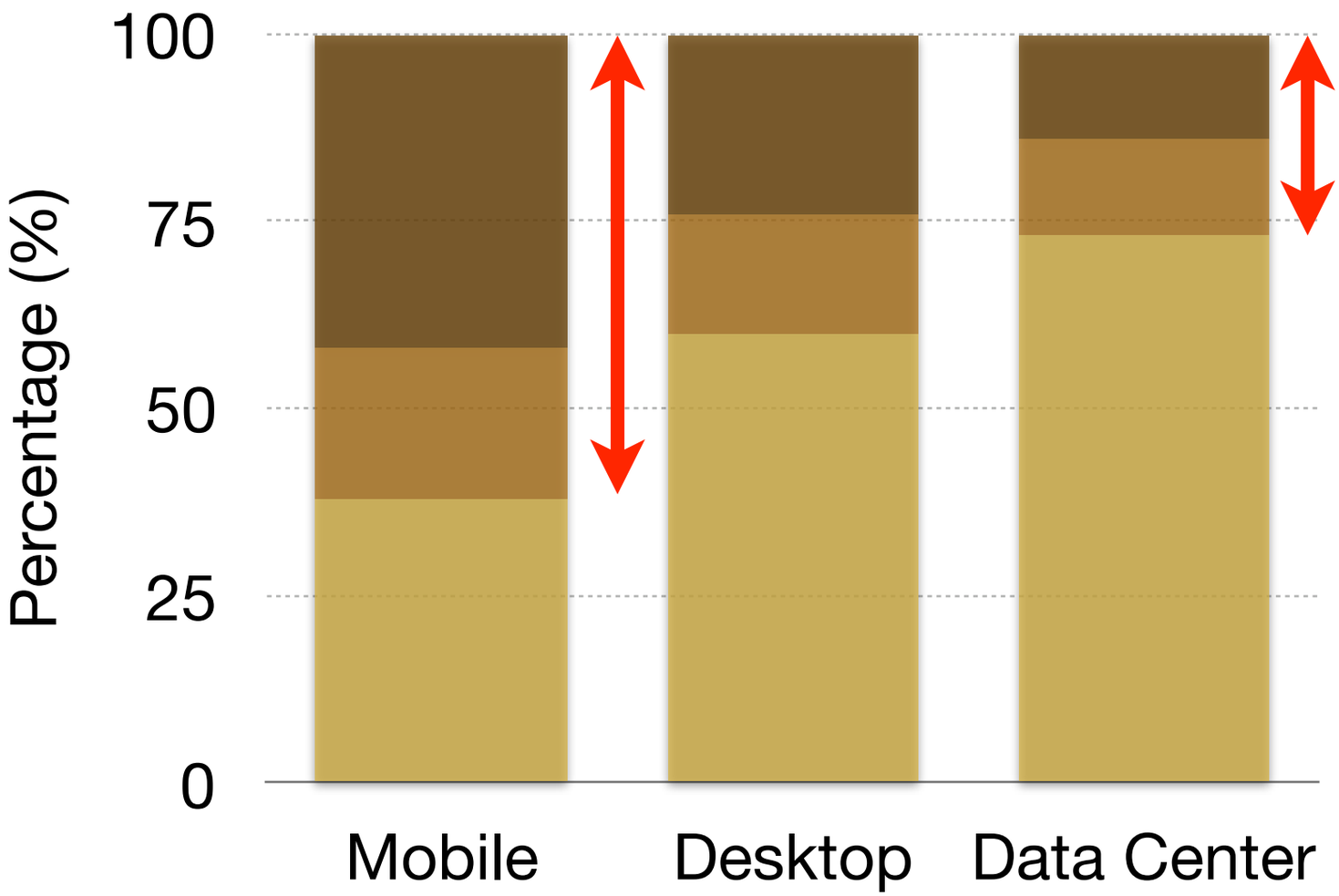

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Developers are Willing to Make Trade-offs

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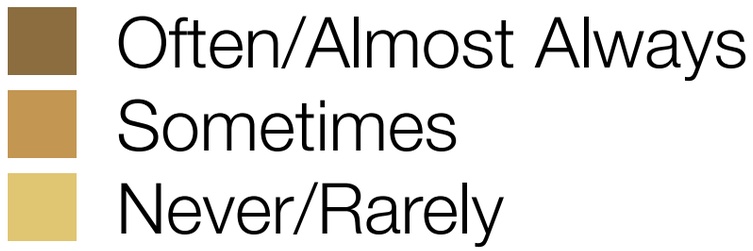
Developers are Willing to Make Trade-offs

"I'm willing to sacrifice performance, etc. for reduced energy usage."



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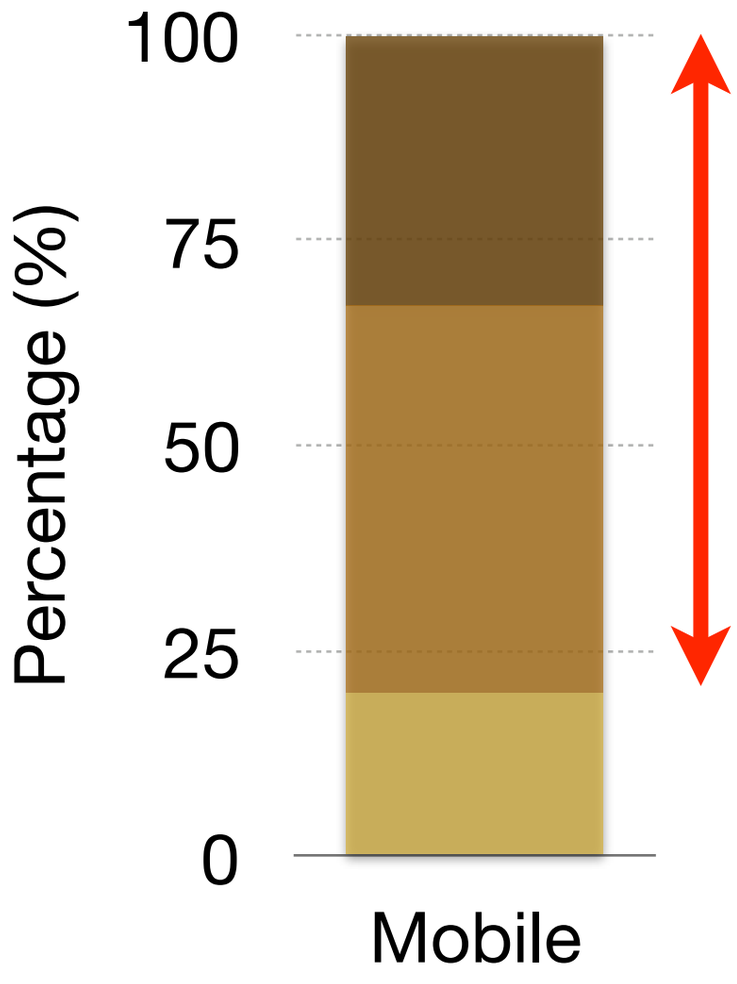

"I'm willing to sacrifice performance, etc. for reduced energy usage."

Often/Almost Always
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Energy-efficiency

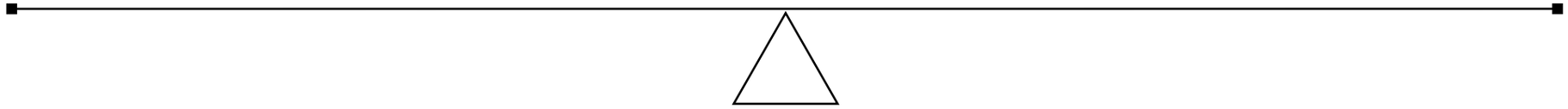
Quality-of-service

Energy-efficiency

Quality-of-service

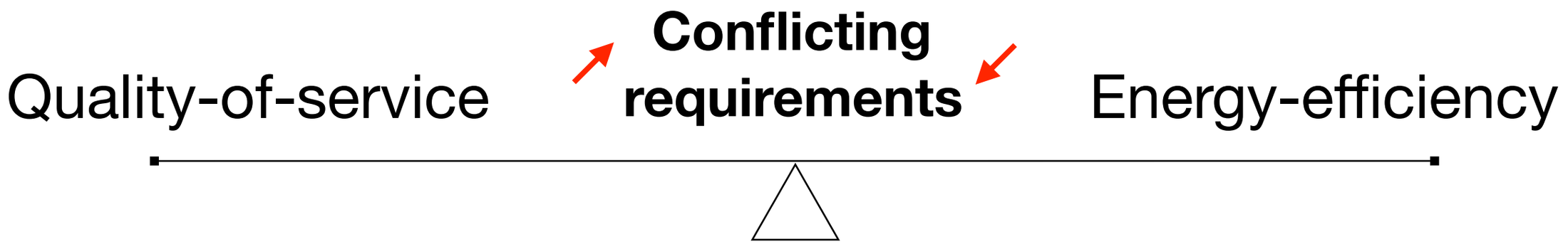
Conflicting requirements

Energy-efficiency



GreenWeb

Programming language support for balancing energy-efficiency and QoS in mobile Web computing



GreenWeb

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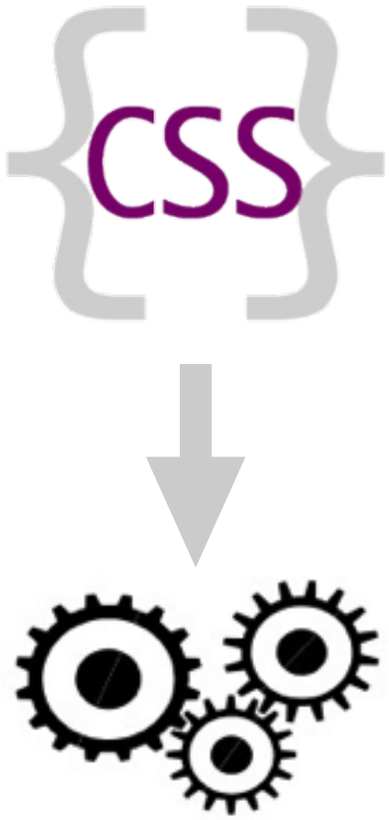
GreenWeb

Programming language support for balancing energy-efficiency and QoS in mobile Web computing

GreenWeb: Language for Energy-Efficiency

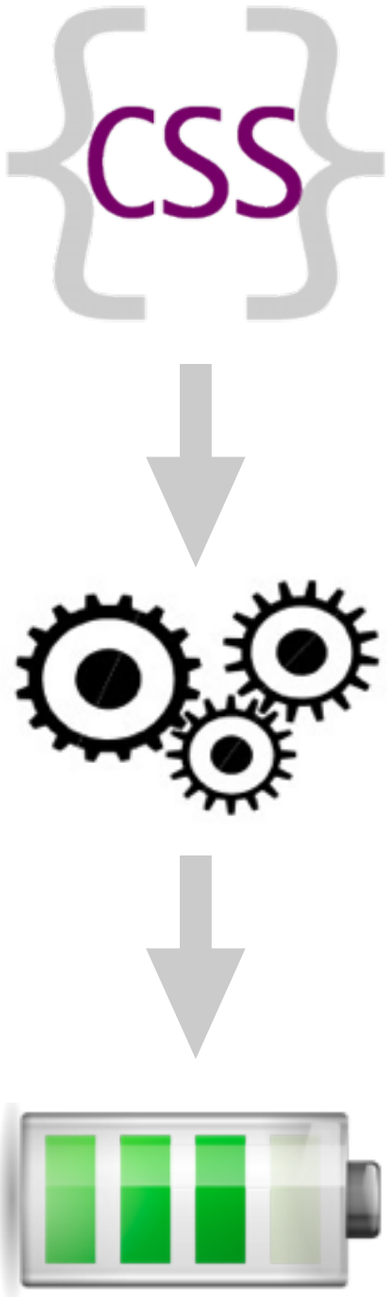
- **Language abstractions** for expressing QoS

GreenWeb: Language for Energy-Efficiency



- **Language abstractions** for expressing QoS
- **Runtime** that saves energy while meeting the QoS constraints

GreenWeb: Language for Energy-Efficiency



- **Language abstractions** for expressing QoS

- **Runtime** that saves energy while meeting the QoS constraints

- **Result** in 60% energy savings on real hardware/software implementations

GreenWeb: Language for Energy-Efficiency

- **Language abstractions** for expressing QoS

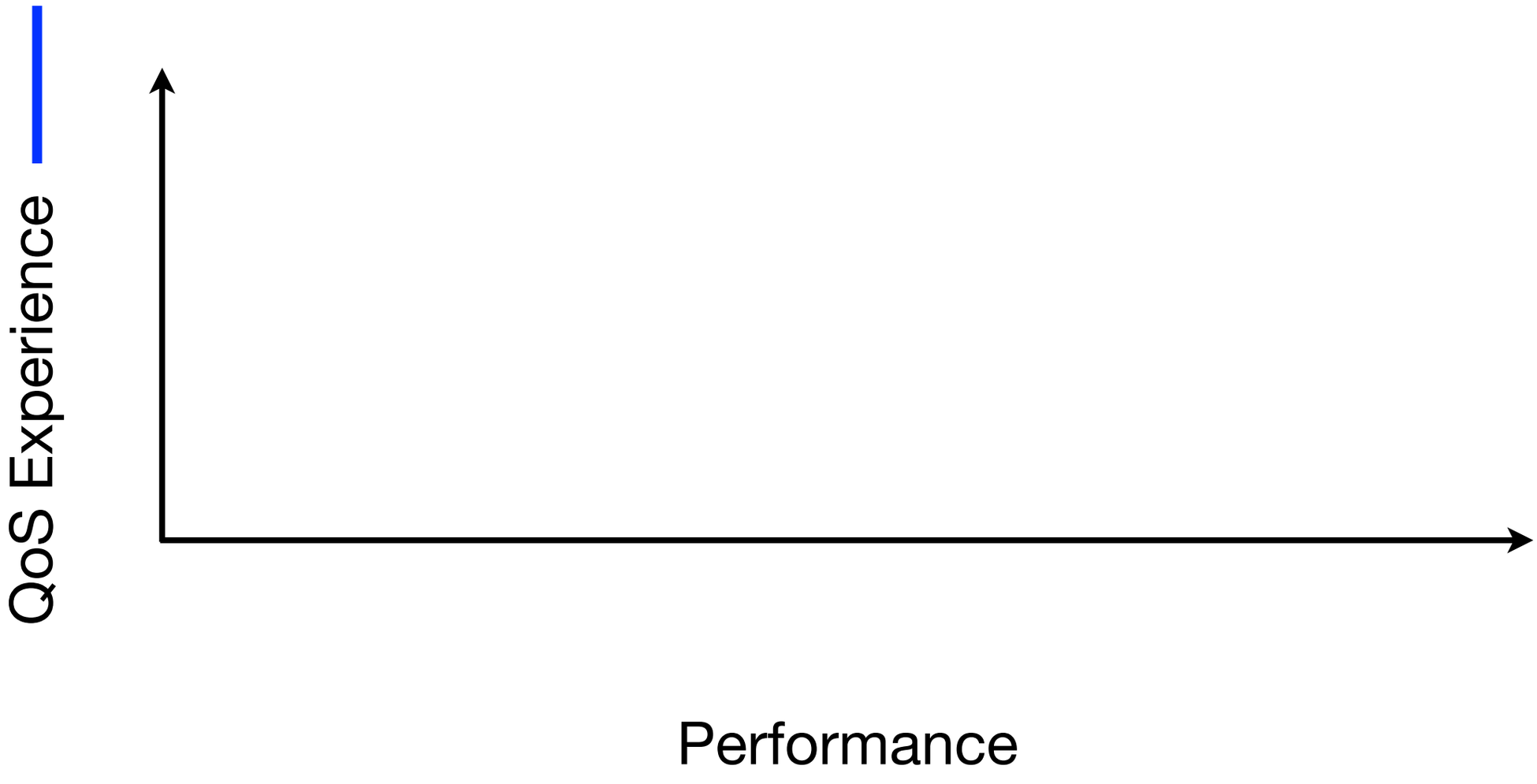
- Runtime
  the QoS constraints

- Result
  hardware/software implementations

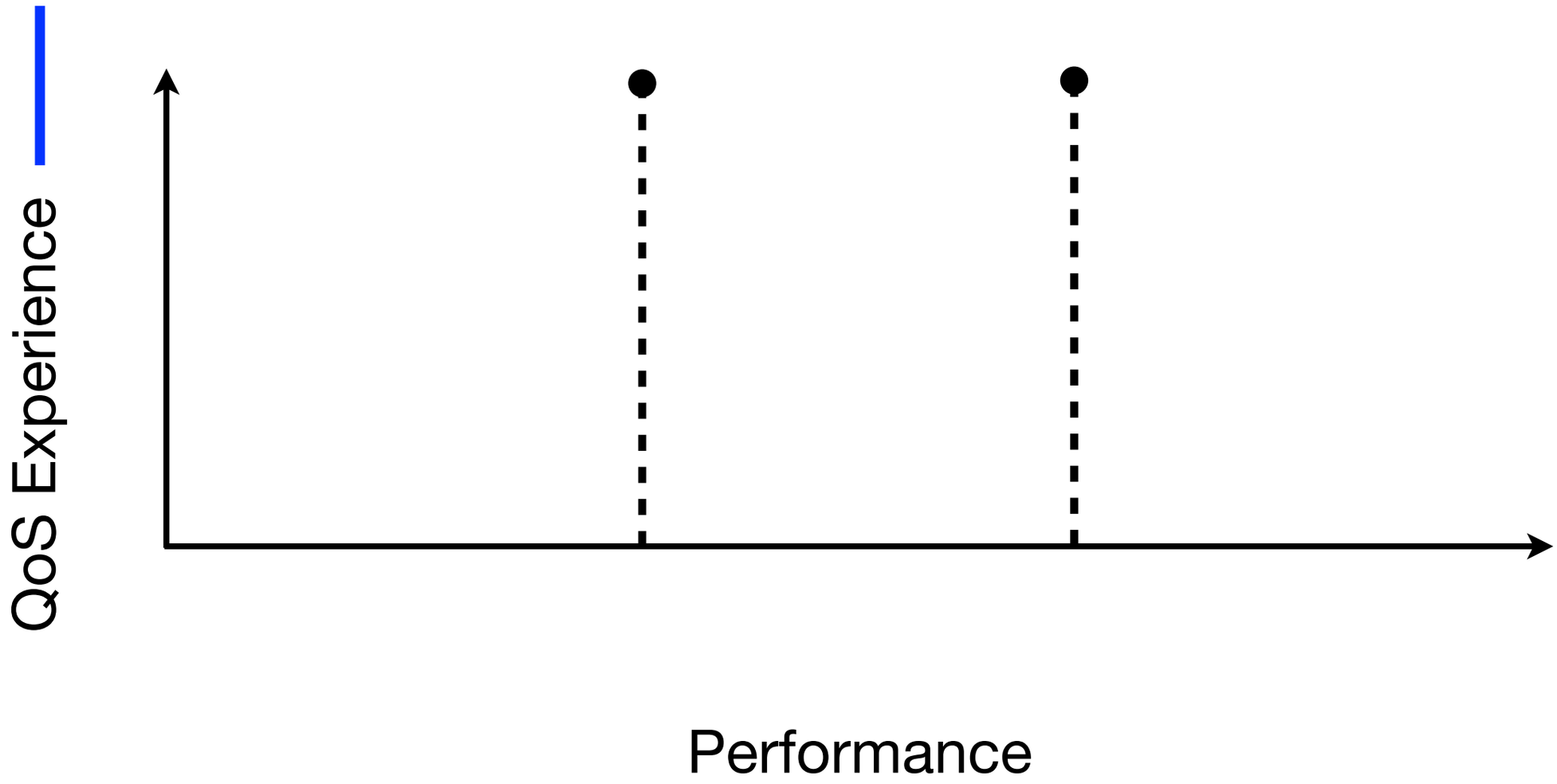
What is QoS in mobile Web?

Understanding Mobile Web QoS

Understanding Mobile Web QoS



Understanding Mobile Web QoS



[OSDI 1996] Y. Endo et al., “Using Latency to Evaluate Interactive System Performance.”

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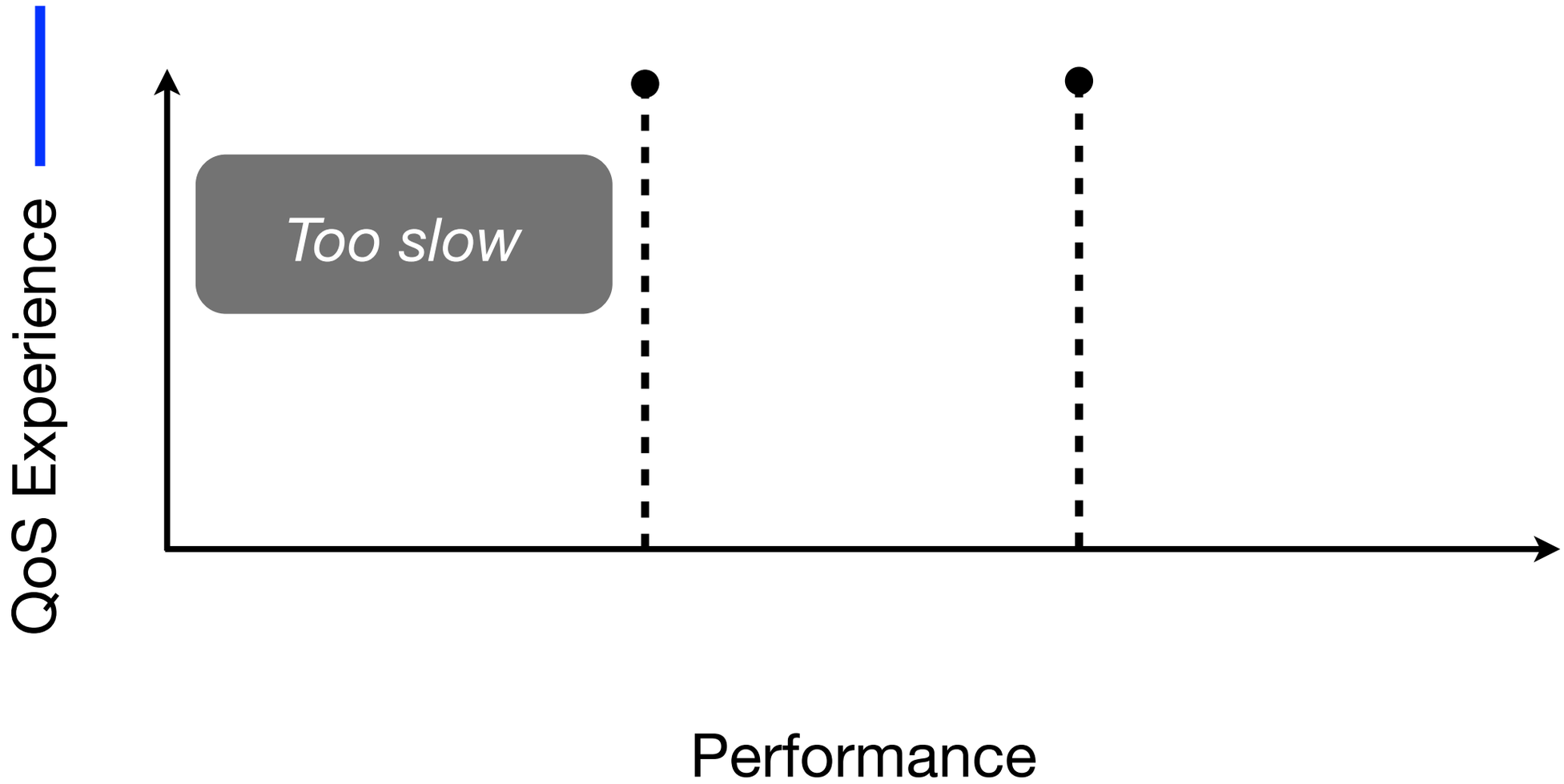

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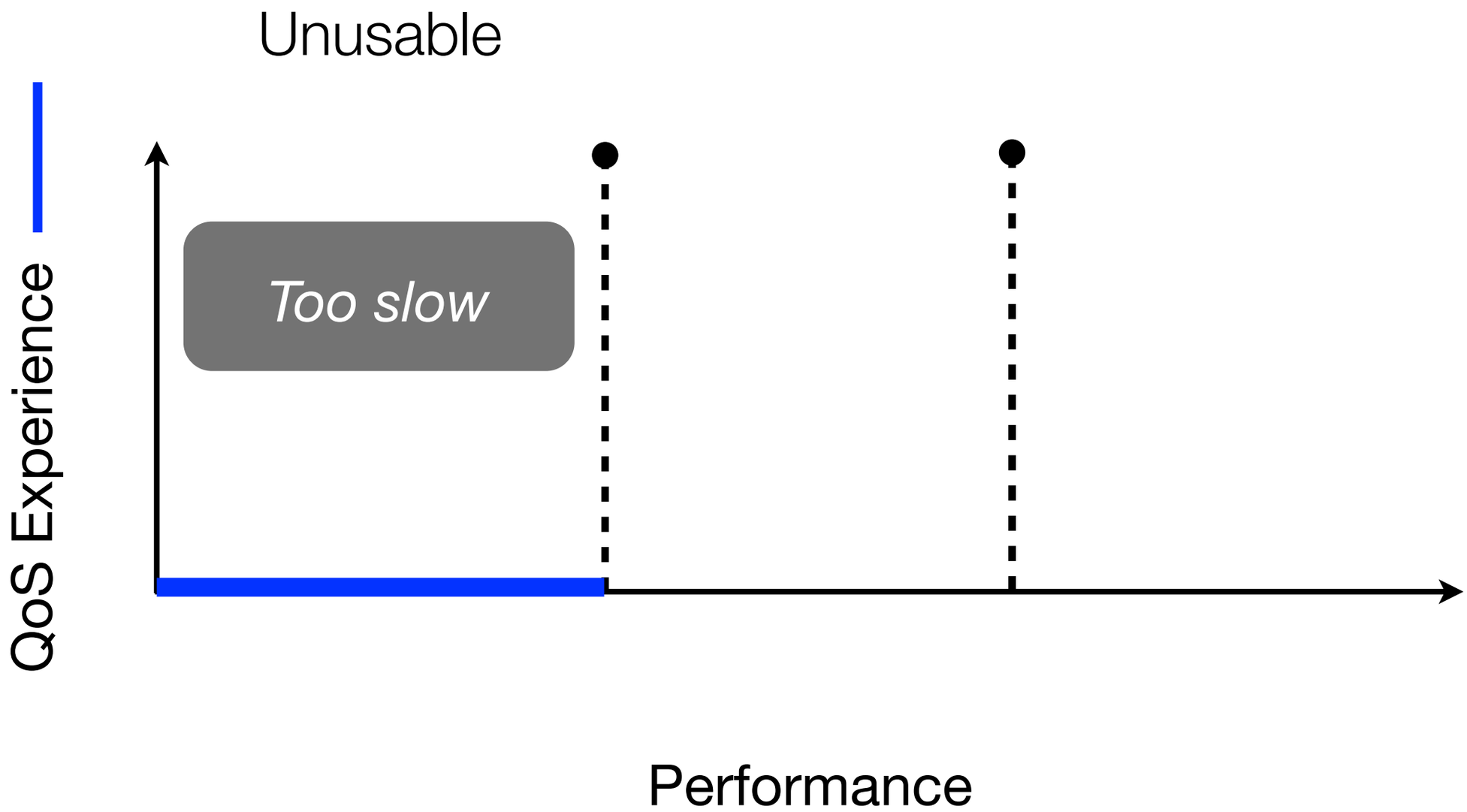

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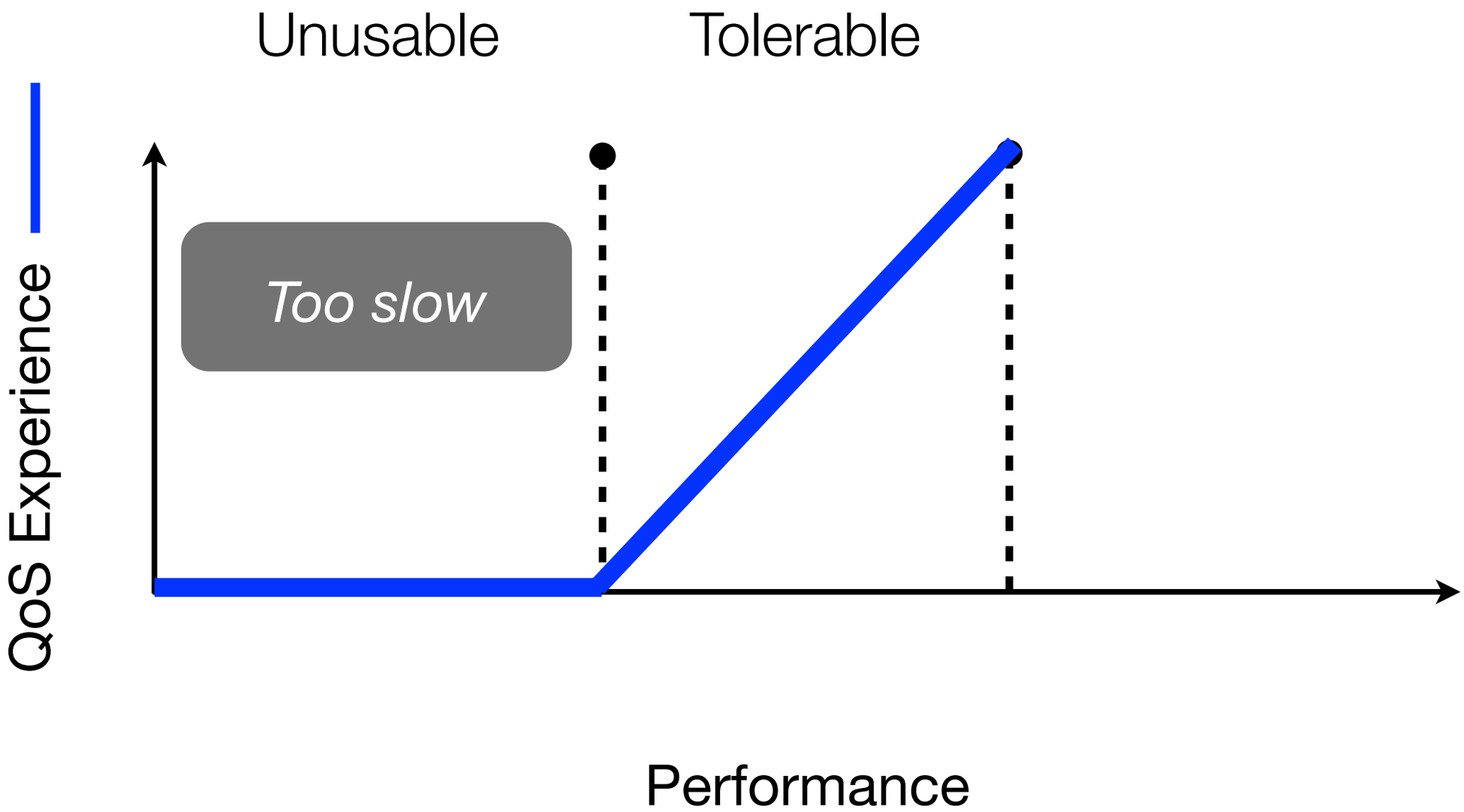

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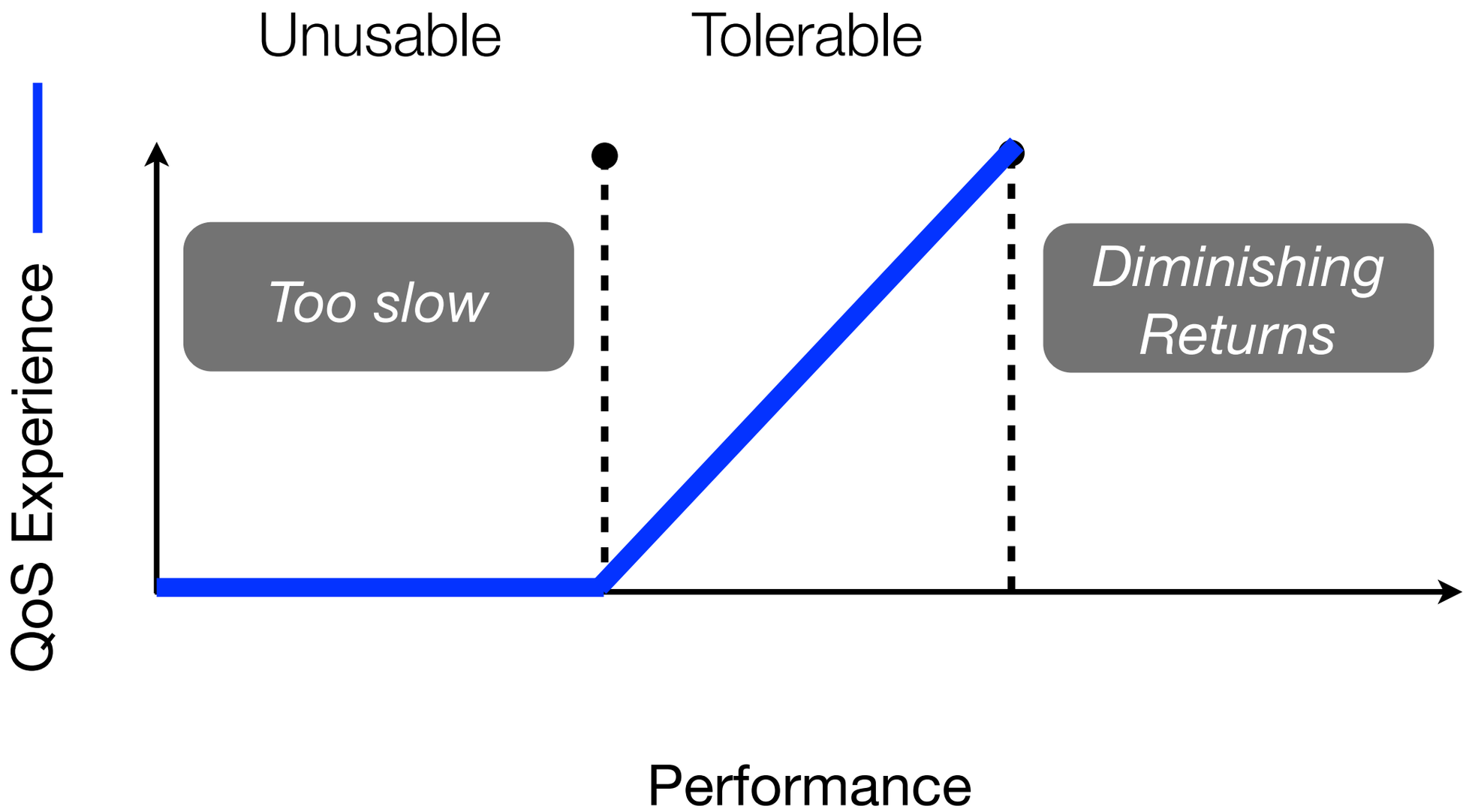

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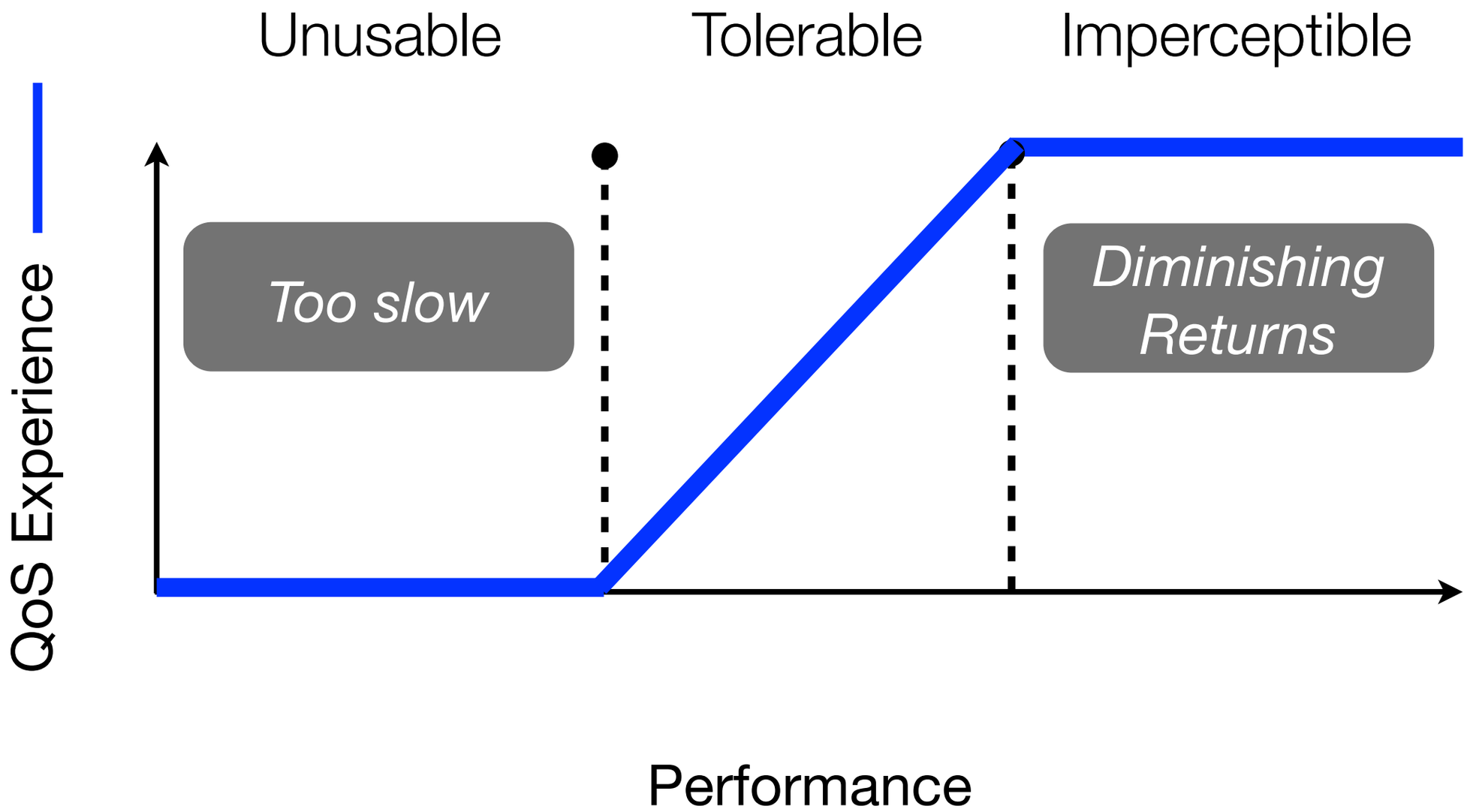

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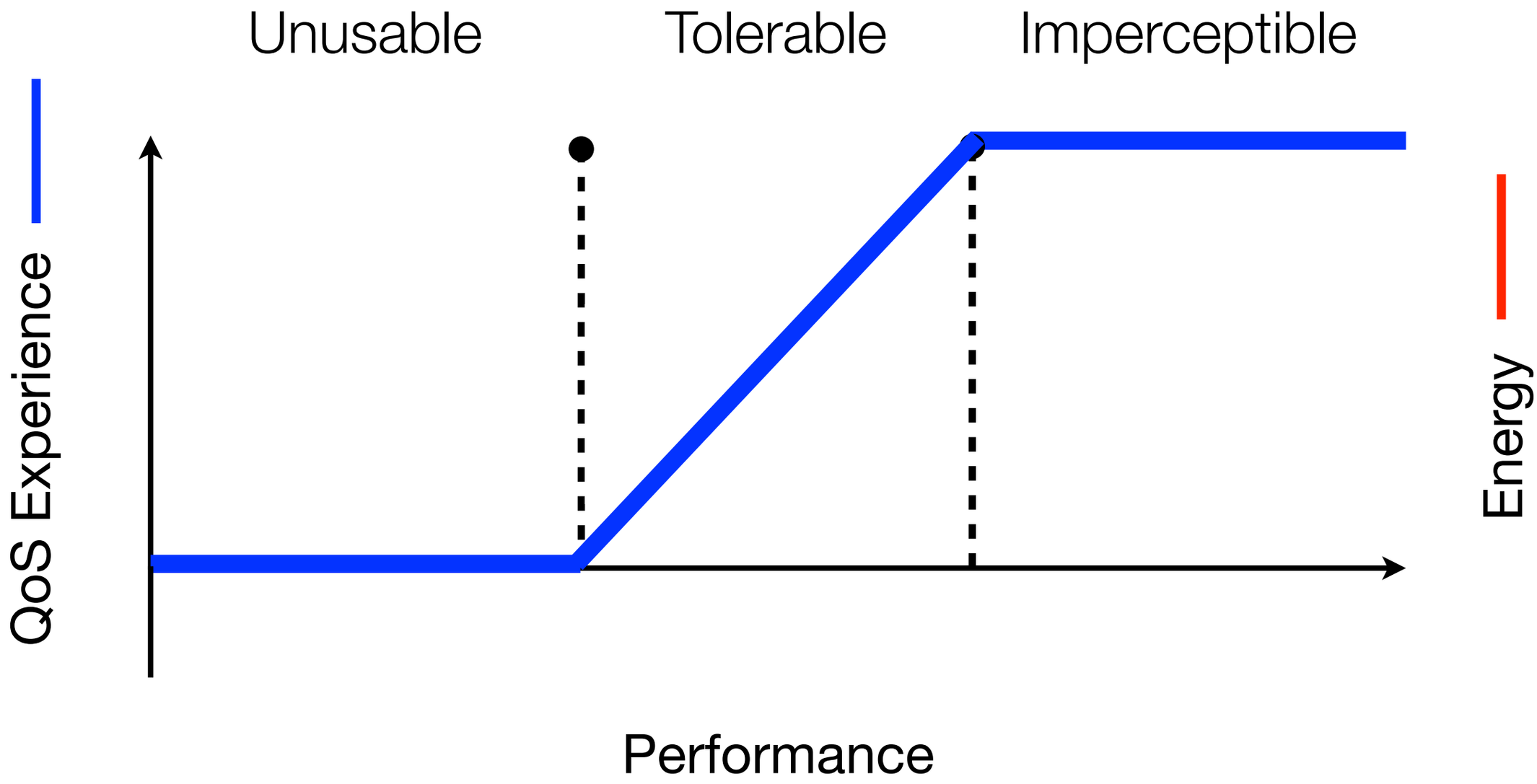

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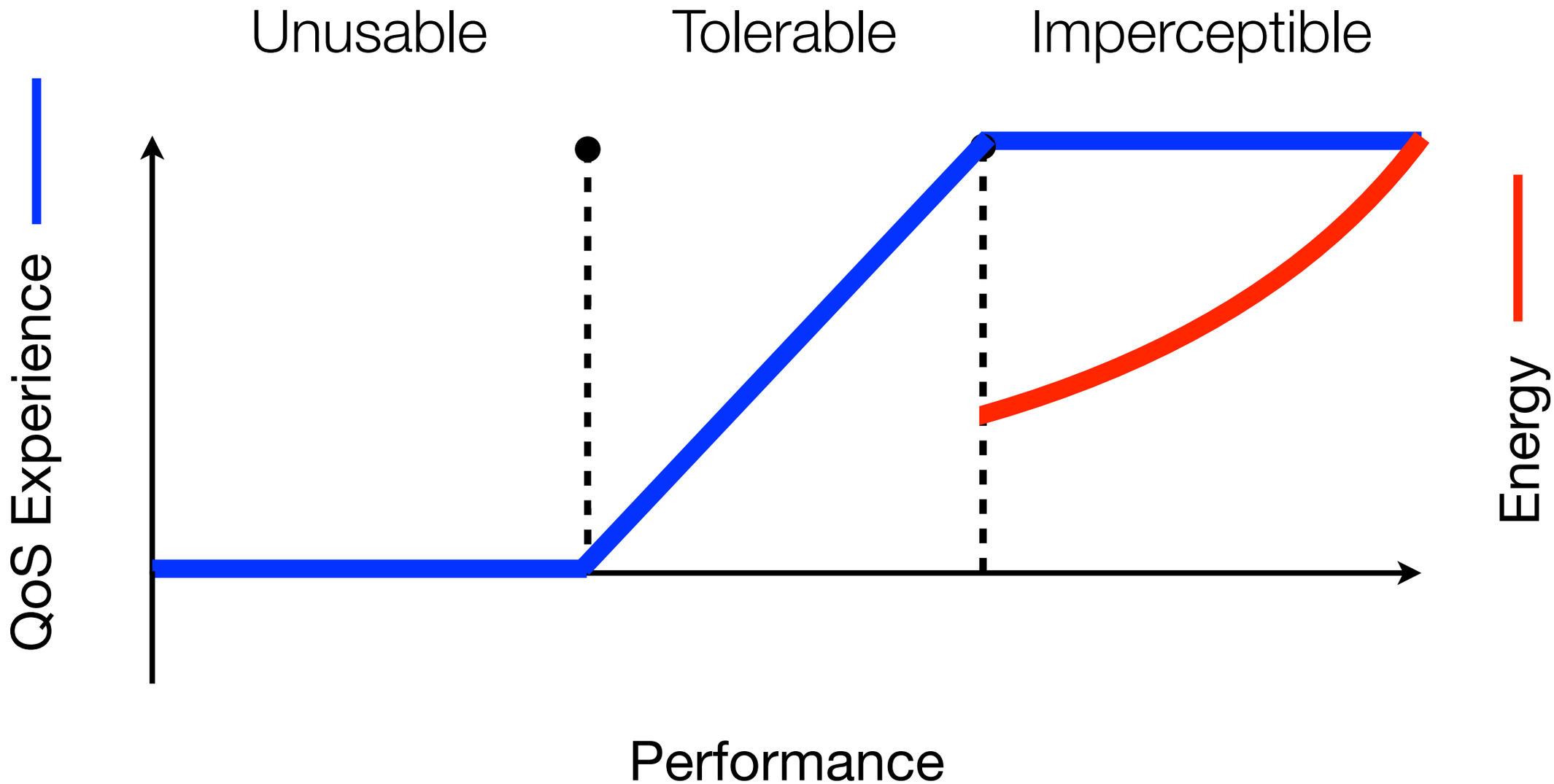

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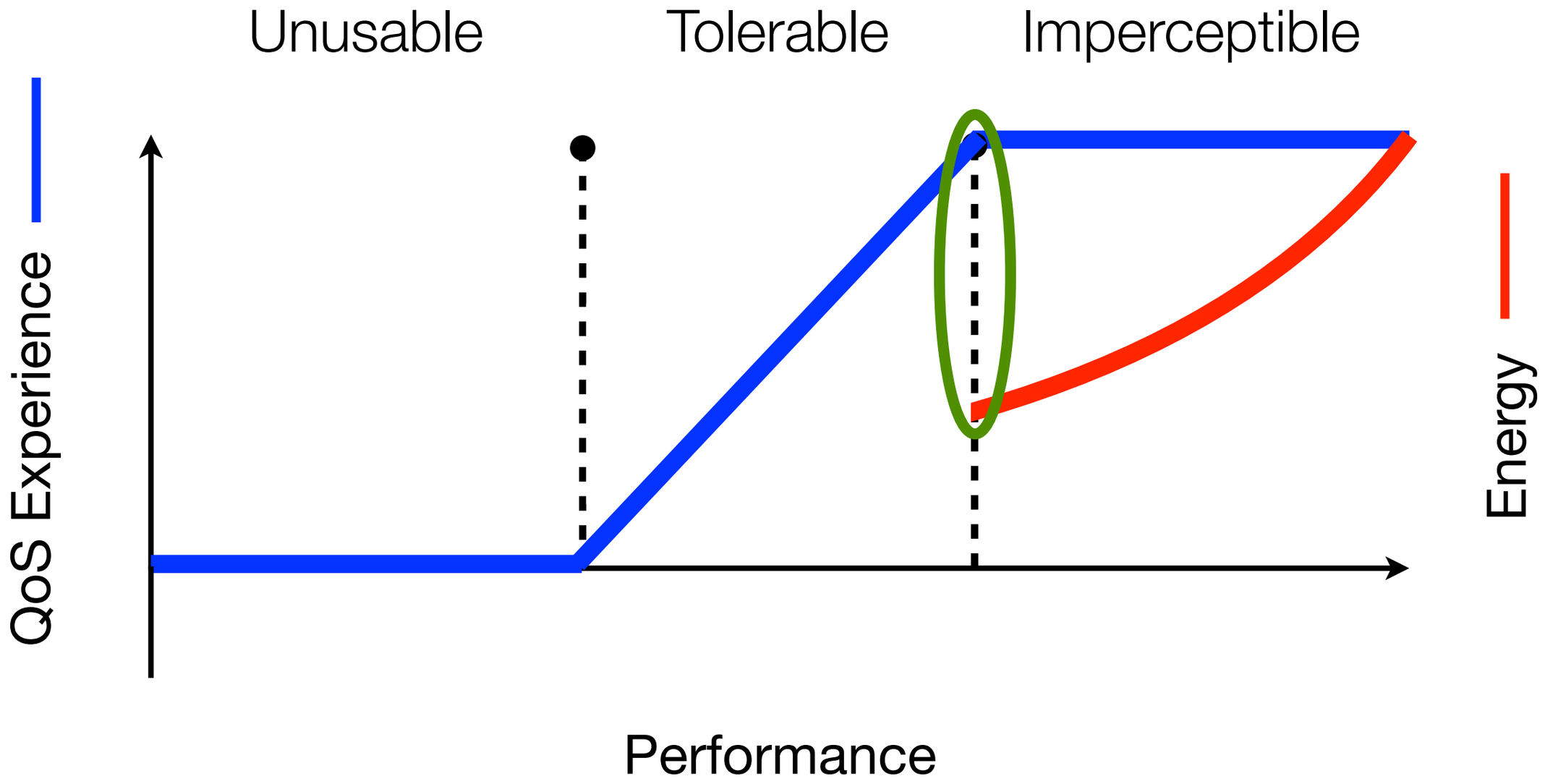

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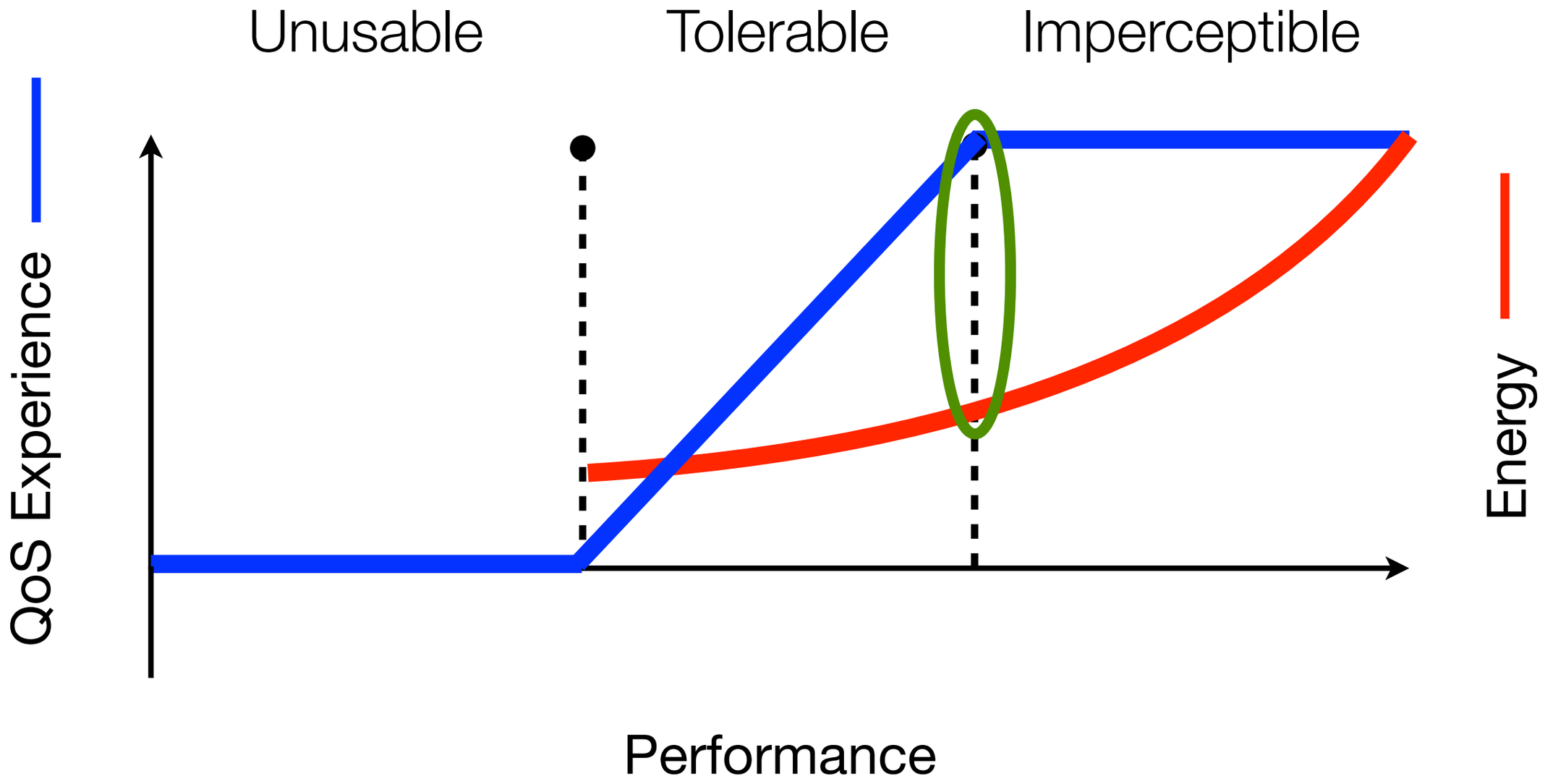

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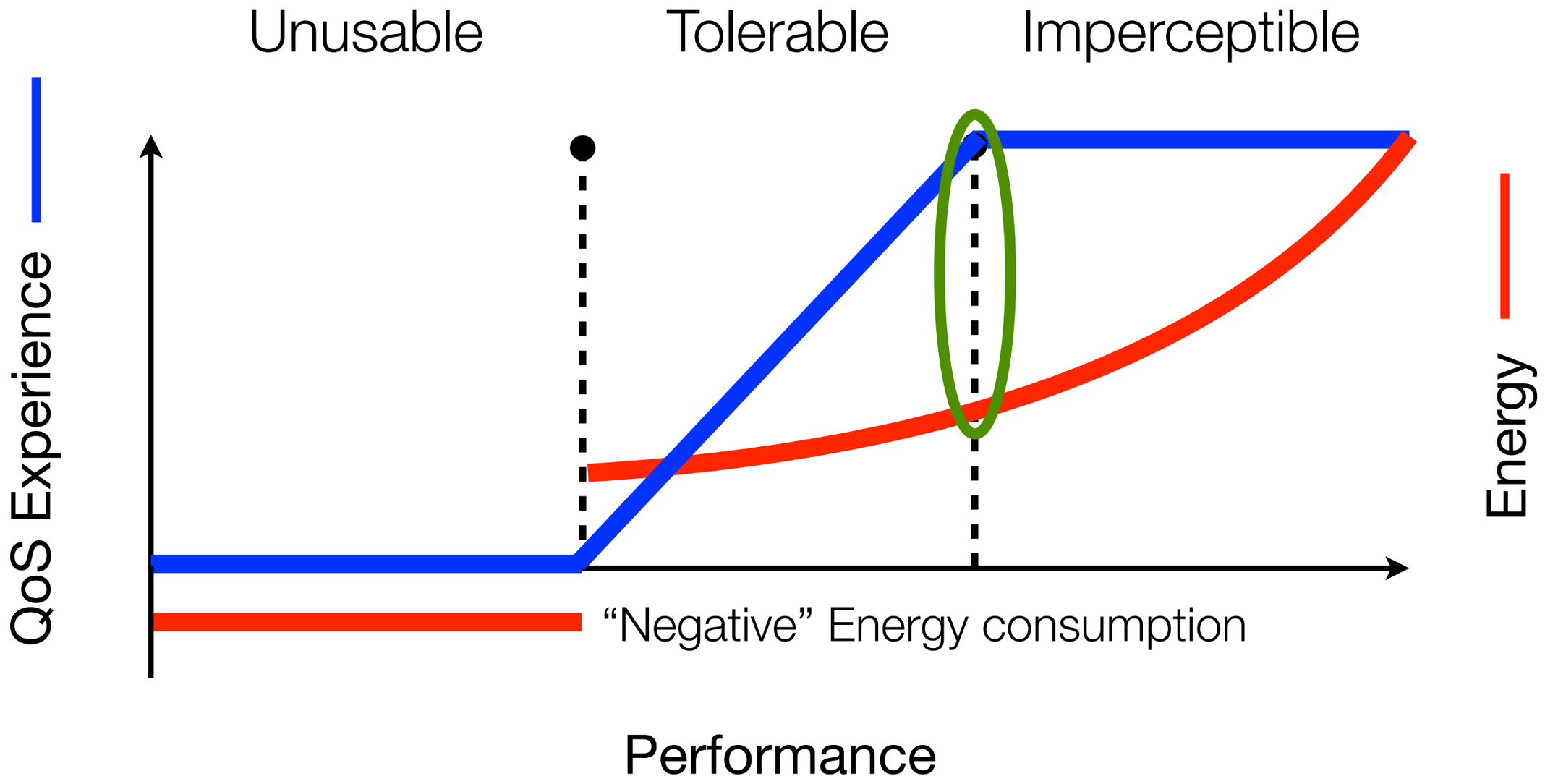

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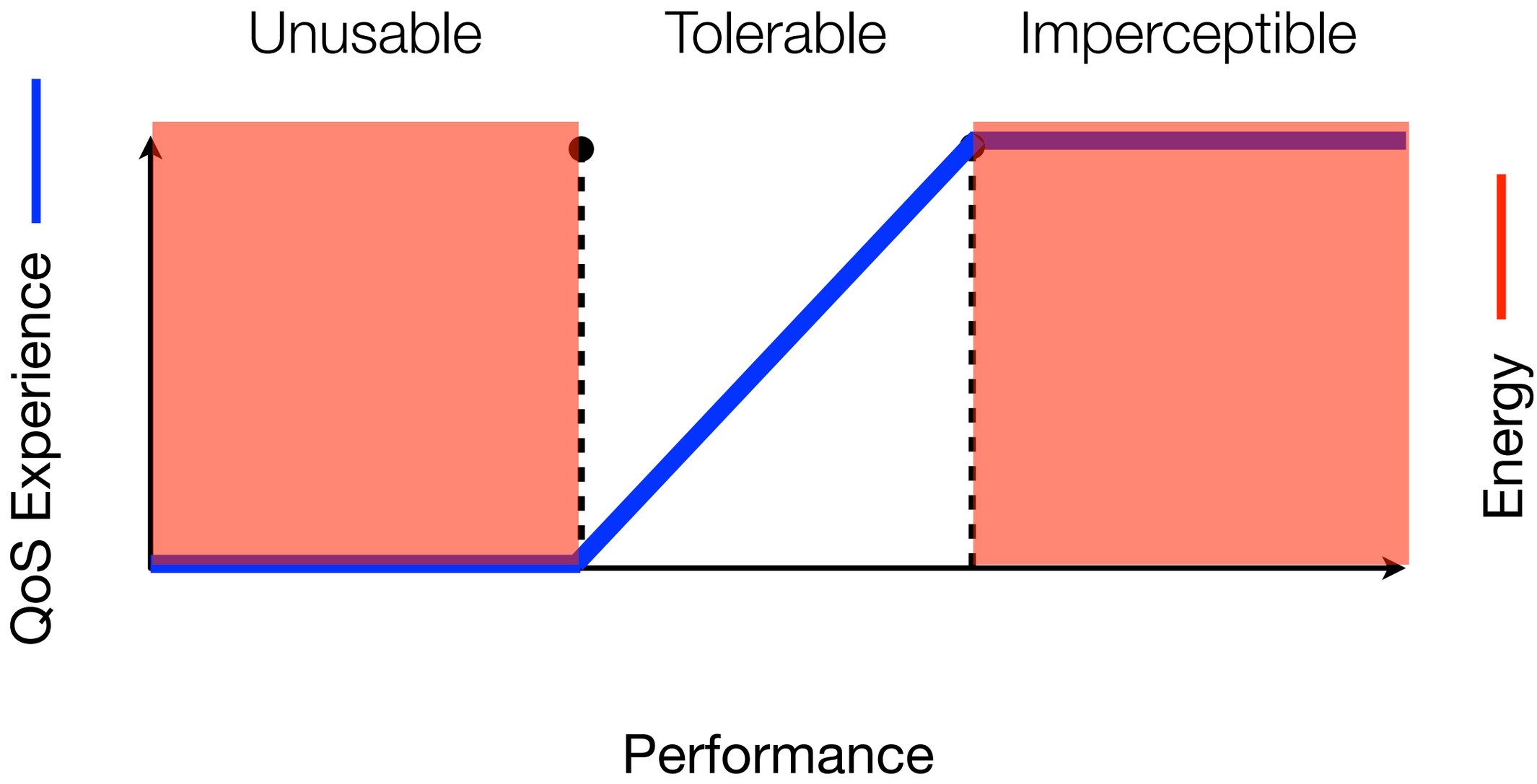

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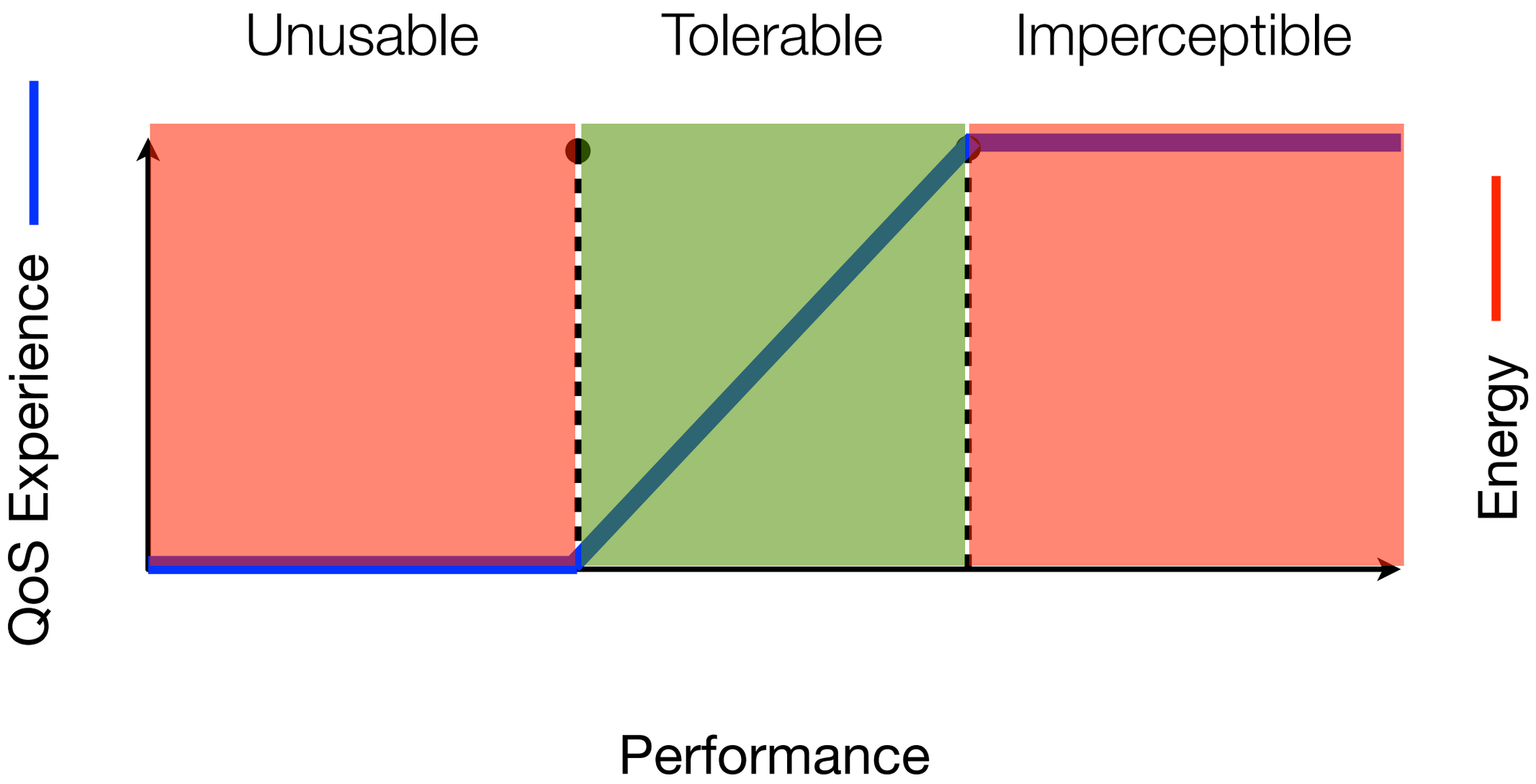

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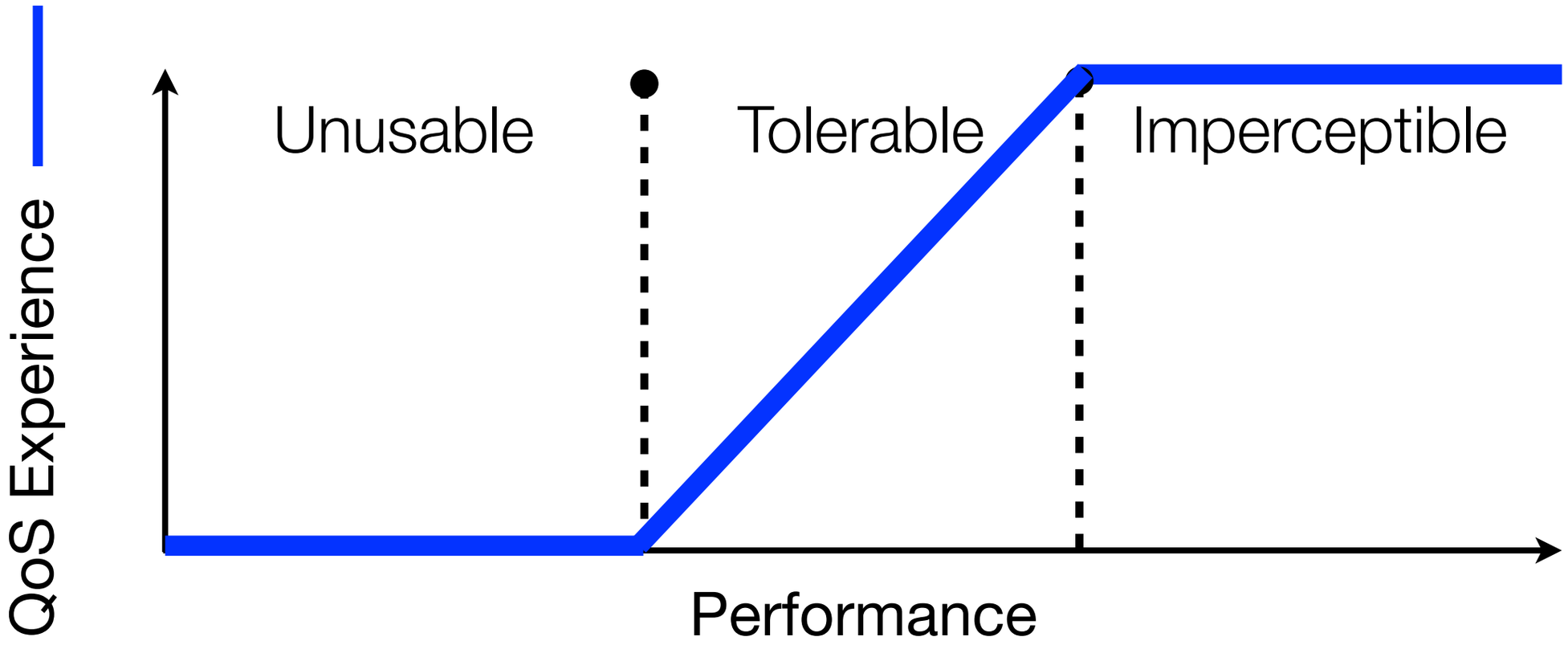
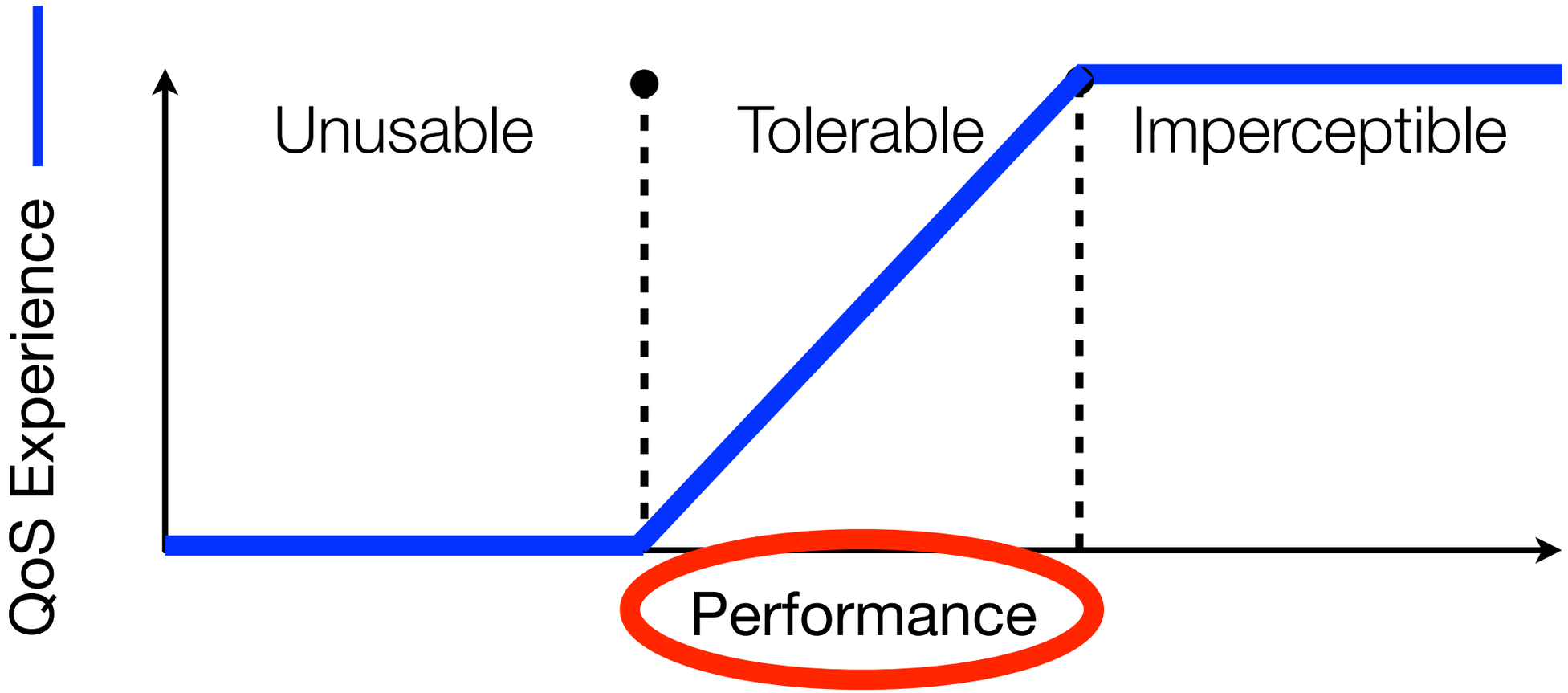
Abstracting Mobile Web QoS



Abstracting Mobile Web QoS

- **Performance metric**
  - Frame latency vs. Frame throughput



Abstracting Mobile Web QoS

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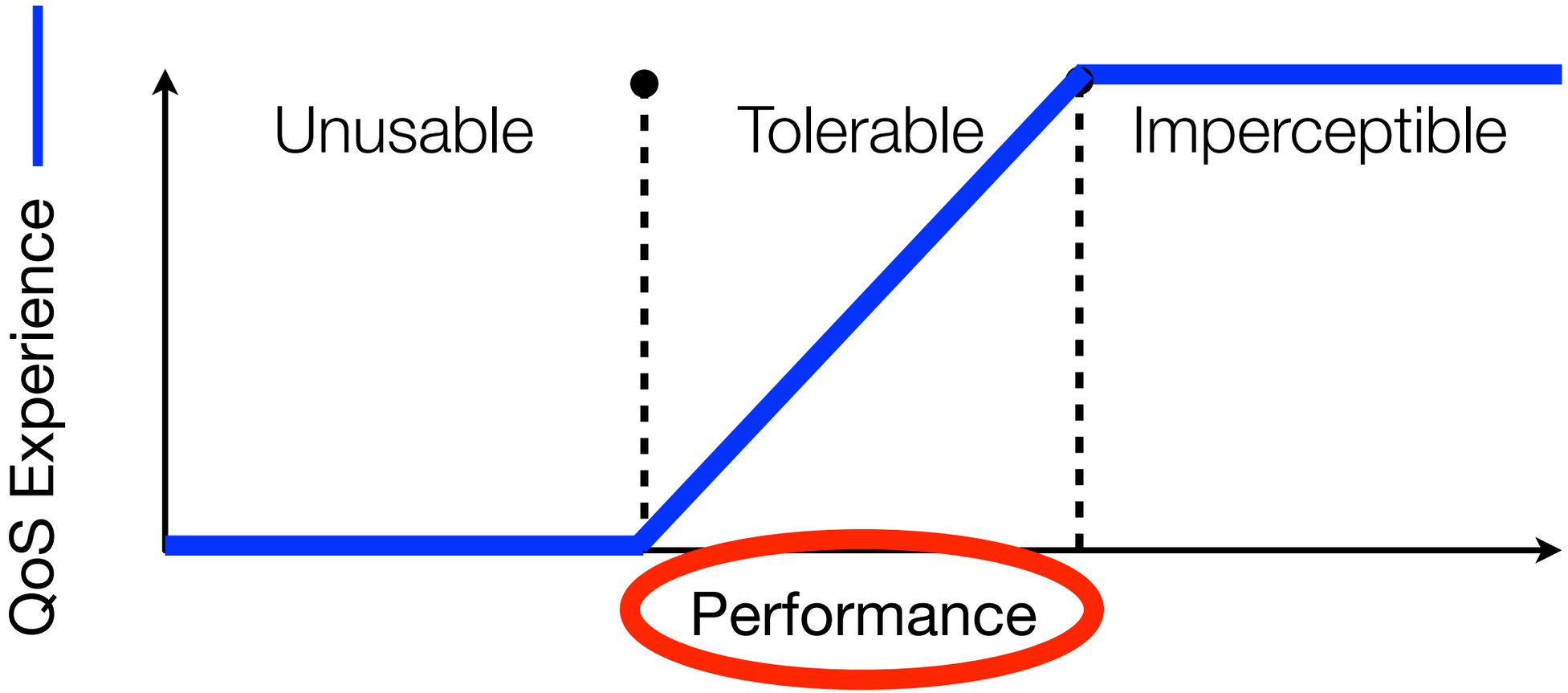
QoS Type



Abstracting Mobile Web QoS

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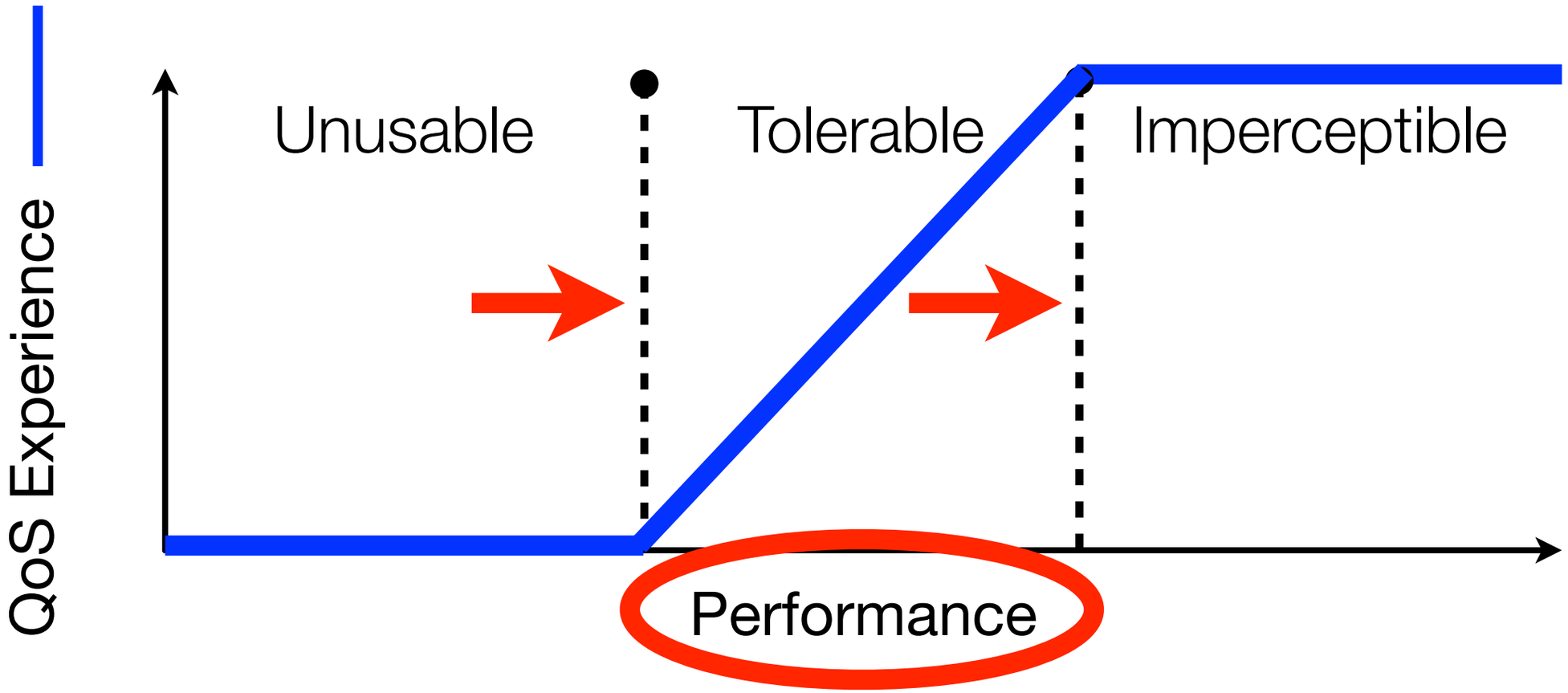
  - Frame latency vs. Frame throughput
- Threshold performance values
  - Imperceptible target vs. Usable target

QoS Type



Abstracting Mobile Web QoS

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QoS Type

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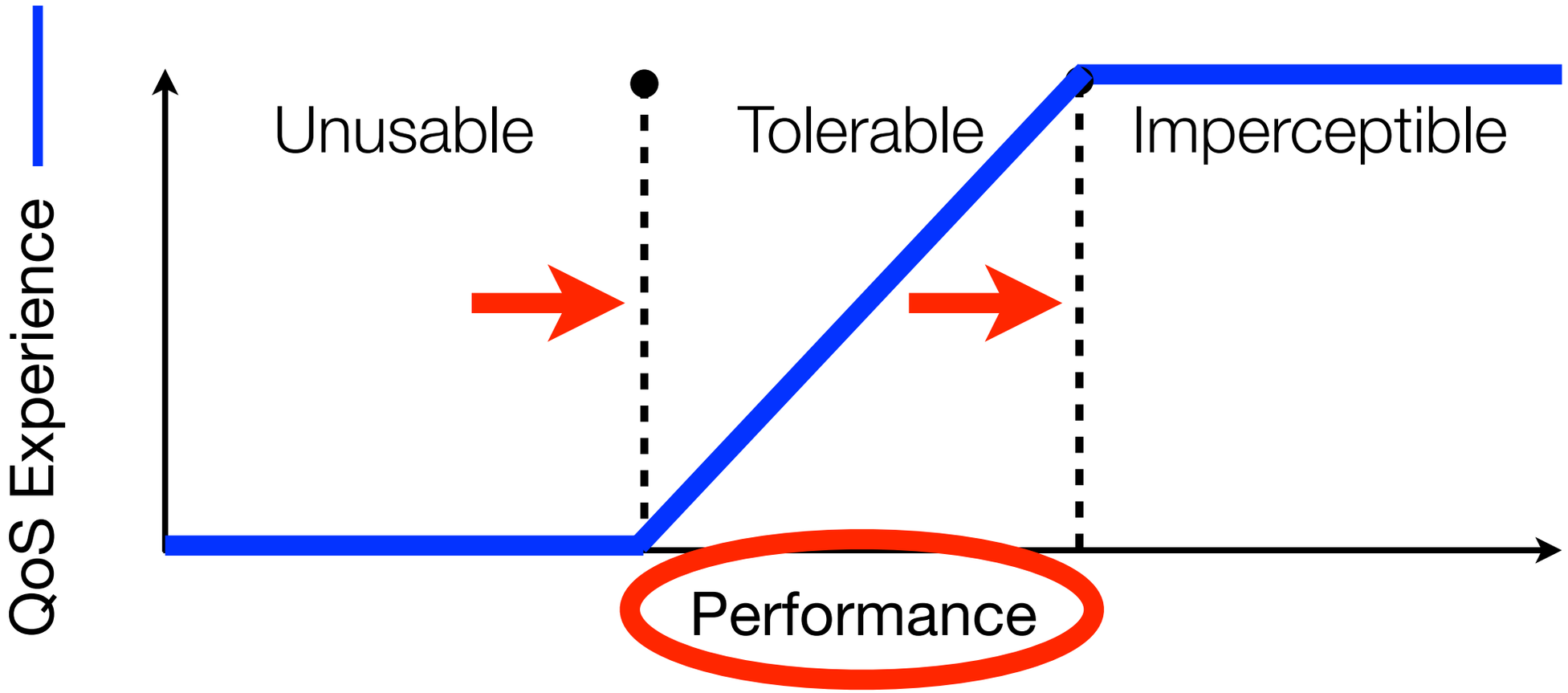
QoS Target



Expressing Mobile Web QoS

Expressing Mobile Web QoS

```
<html> <head>
  <script>
    function animateMove() {
      /* Animation code omitted */
    }
  </script> </head> <body>
  <div ontouchend="animateMove()">
  <div/> <!– other elements -->
</body> </html>
```

Expressing Mobile Web QoS

element

```
<html> <head>
  <script>
    function animateMove() {
      /* Animation code omitted */
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Expressing Mobile Web QoS

element **event**

```
<html> <head>
  <script>
    function animateMove() {
      /* Animation code omitted */
    }
  </script> </head> <body>
  <div ontouchend=“animateMove()”>
  <div/> <!– other elements -->
</body> </html>
```

Expressing Mobile Web QoS

element **event**

```
<html> <head>
  <script>
    function animateMove() {
      /* Animation code omitted */
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  </script> </head> <body>
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Expressing Mobile Web QoS

element **event**

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<html> <head>
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</script> </head> <body>
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<div/> <!– other elements -->
</body> </html>
```

Expressing QoS at an event granularity

Expressing Mobile Web QoS

Annotation

```
                element   event

<html> <head>
  <style>


  </style>
  <script>
   function animateMove() {
     /* Animation code omitted */
   }
  </script> </head> <body>
  <div ontouchend="animateMove()">
  <div/> <!— other elements -->
</body> </html>
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Expressing Mobile Web QoS

Annotation

```
                element   event

<html> <head>
  <style>
    div {
      ontouchend
    }
  </style>
  <script>
   function animateMove() {
     /* Animation code omitted */
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  <div ontouchend="animateMove()">
  <div/> <!— other elements -->
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```

Expressing Mobile Web QoS

Annotation

```
element {event: Type, Target}
```

```
<html> <head>
  <style>
    div {
      ontouchend: throughput, low;
    }
  </style>
  <script>
   function animateMove() {
     /* Animation code omitted */
   }
  </script> </head> <body>
  <div ontouchend="animateMove()">
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Expressing Mobile Web QoS


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Expressing Mobile Web QoS


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  <div ontouchend="animateMove()">
  <div/> <!– other elements -->
</body> </html>
```

Expressing Mobile Web QoS


```
element {event: Type, Target}
```

Annotation

```
<html> <head>
  <style>
    div {
      ontouchend: throughput, low;
    }
  </style>
  <script>
    function newAnimateMove() {
      /* New animation code */
    }
  </script> </head> <body>
  <div ontouchend="animateMove()">
  <div/> <!— other elements -->
</body> </html>
```

Expressing Mobile Web QoS


```
element {event: Type, Target}
```

Annotation

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<html> <head>
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</body> </html>
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Implementation independent

Expressing Mobile Web QoS


```
element {event: Type, Target}
```

Annotation

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<html> <head>
  <style>
    div {
      ontouchend: throughput, low;
    }
  </style>
  <script>
    function newAnimateMove() {
      /* New animation code */
    }
  </script> </head> <body>
  <div ontouchend="animateMove()">
  <div/> <!– other elements -->
</body> </html>
```

Implementation independent

Expressing Mobile Web QoS

CSS
Cascading Style Sheet

```
element {event: Type, Target}
```

Annotation

```
<html> <head>
  <style>
    div {
      ontouchend: throughput, low;
    }
  </style>
  <script>
    function newAnimateMove() {
      /* New animation code */
    }
  </script> </head> <body>
  <div ontouchend="animateMove()">
  <div/> <!– other elements -->
</body> </html>
```

Implementation independent

Non-interfering w.r.t. functionality

GreenWeb Annotation Process

Original application

Manual Annotation

GreenWeb-annotated application

GreenWeb Annotation Process

Original application

Automatic Annotation?

GreenWeb-annotated application

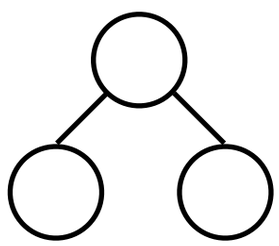
GreenWeb Annotation Process

- **AutoGreen**: *automatically* reasons about and inserts **GreenWeb** annotations

GreenWeb Annotation Process

- **AutoGreen**: *automatically* reasons about and inserts **GreenWeb** annotations

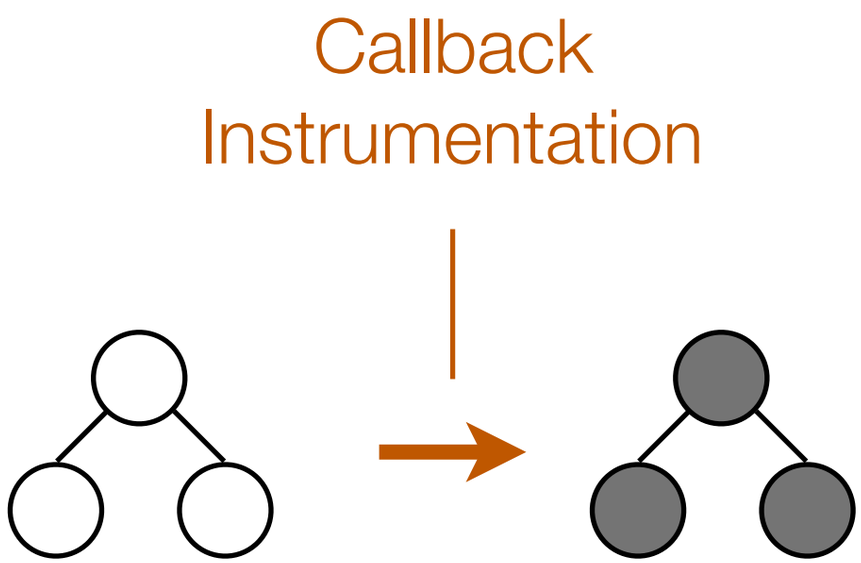
GreenWeb Annotation Process



GreenWeb-annotated application

- **AutoGreen**: *automatically* reasons about and inserts **GreenWeb** annotations

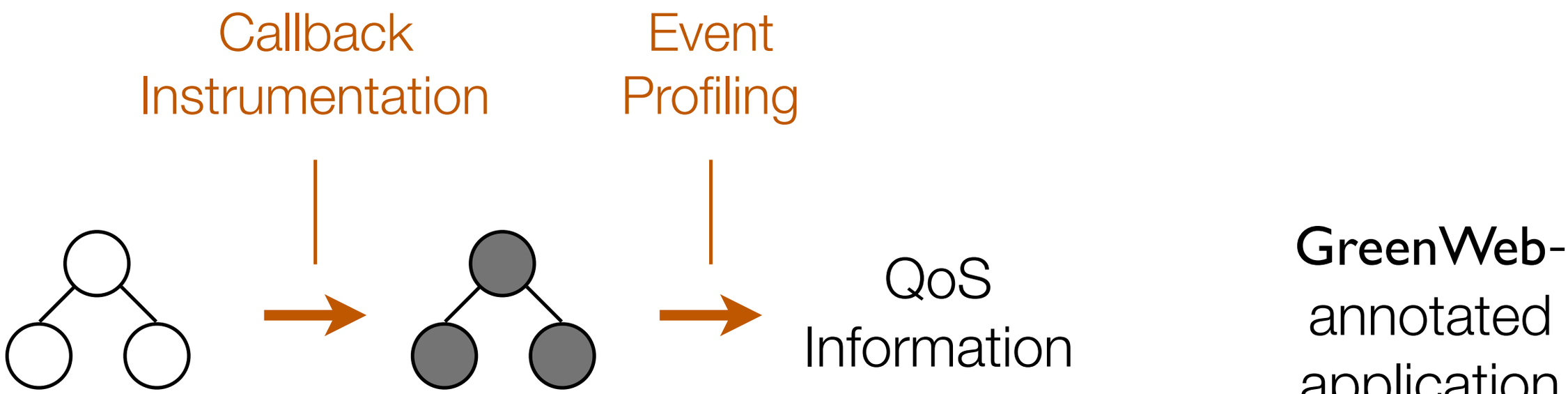
GreenWeb Annotation Process



GreenWeb-annotated application

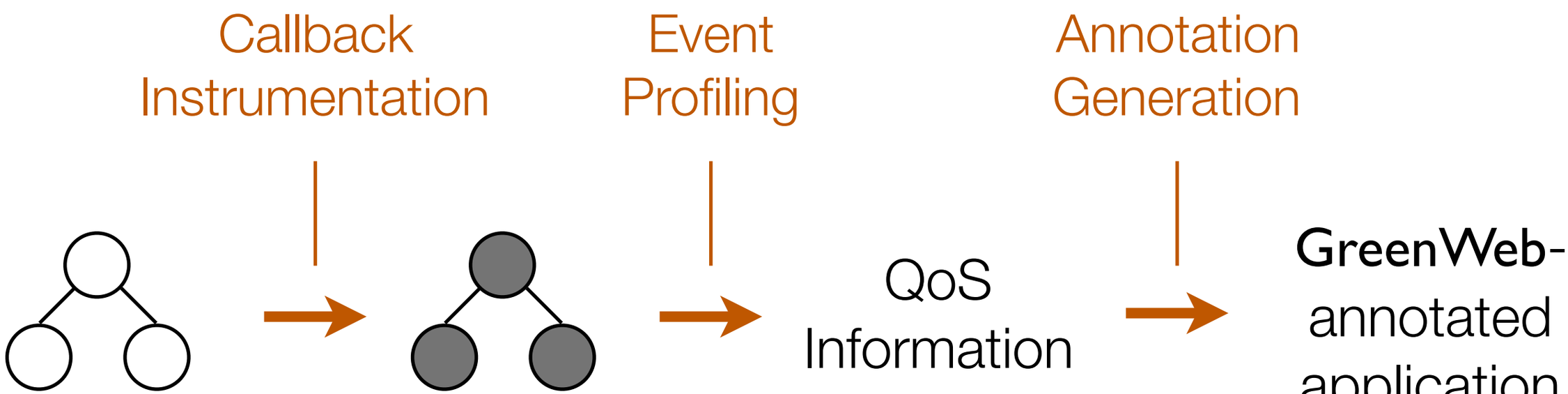
- **AutoGreen**: *automatically* reasons about and inserts **GreenWeb** annotations

GreenWeb Annotation Process



- **AutoGreen**: *automatically* reasons about and inserts **GreenWeb** annotations

GreenWeb Annotation Process



- **AutoGreen**: *automatically* reasons about and inserts **GreenWeb** annotations

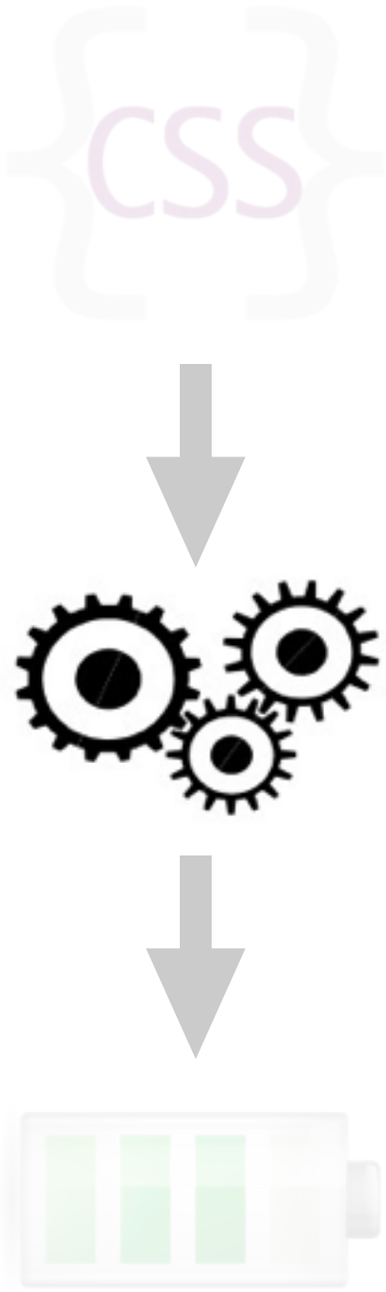
GreenWeb: Language for Energy-Efficiency

- **Language abstractions** for expressing QoS

- Runtime
  the QoS constraints

- Result
  hardware/software implementations

GreenWeb: Language for Energy-Efficiency



- Language abstractions
- **Runtime** that saves energy while meeting the QoS constraints
- Result
  hardware/software implementations

GreenWeb Runtime Overview

GreenWeb Runtime Overview

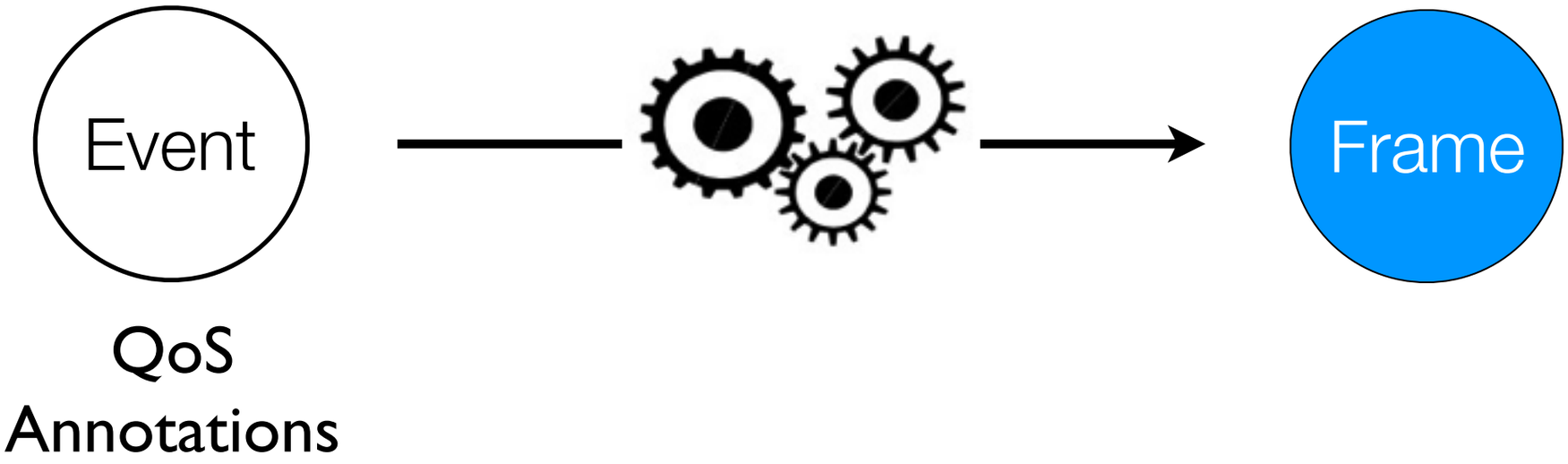
GreenWeb Runtime Overview

QoS
Annotations

GreenWeb Runtime Overview

Runtime Objective

Enforcing event-level QoS at the frame-level energy-efficiently



GreenWeb Runtime Overview

Runtime Objective

Enforcing event-level QoS at the frame-level energy-efficiently

QoS type: latency

QoS target: 16 ms

GreenWeb Runtime Overview

Runtime Objective

Enforcing event-level QoS at the frame-level energy-efficiently

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GreenWeb Runtime Overview

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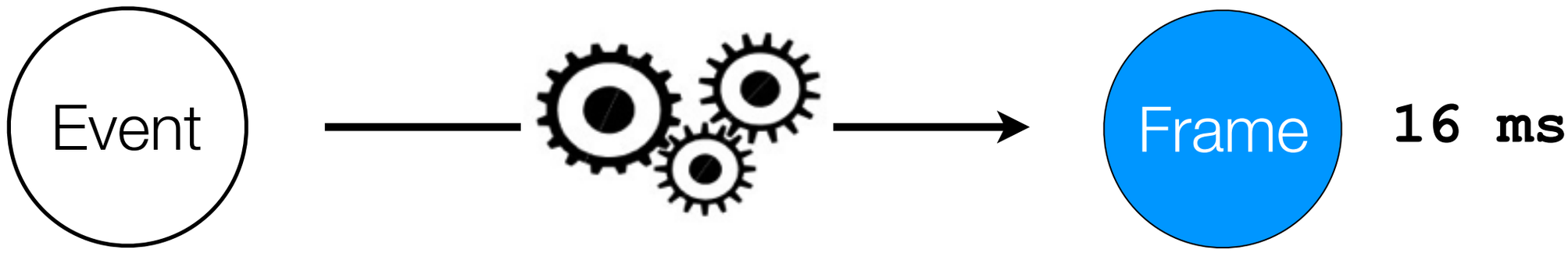

QoS type: latency

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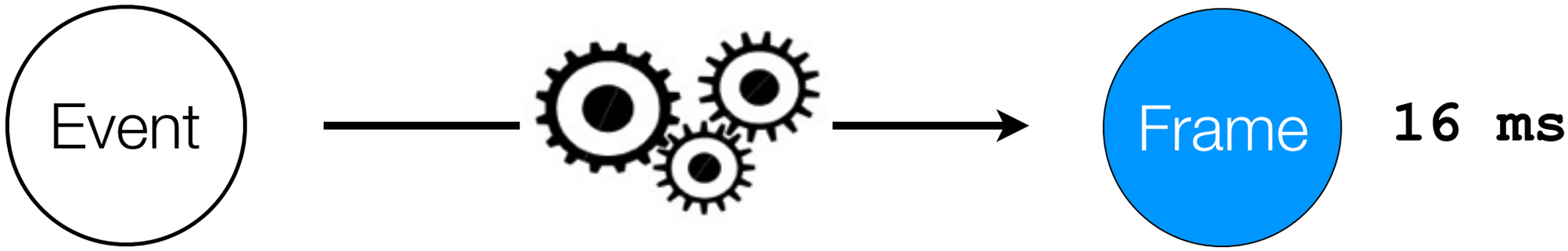
GreenWeb Runtime Overview

Runtime Objective

Enforcing event-level QoS at the frame-level energy-efficiently



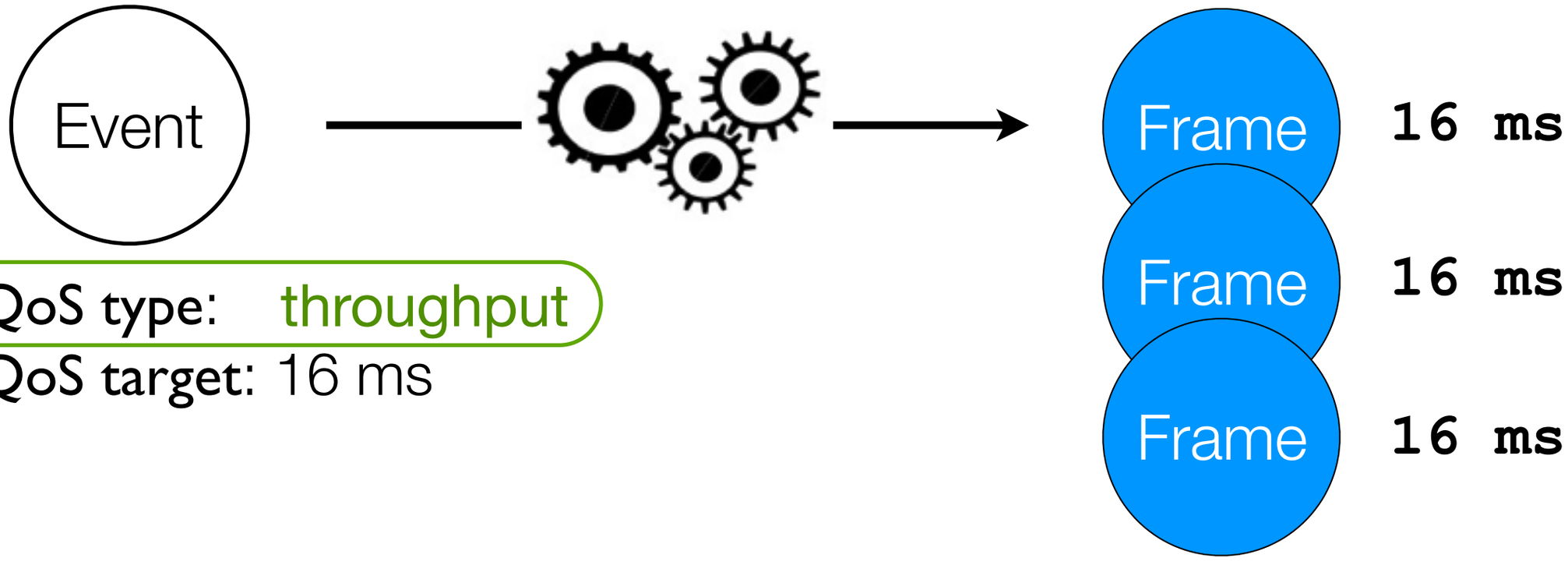
QoS type: throughput

QoS target: 16 ms

GreenWeb Runtime Overview

Runtime Objective

Enforcing event-level QoS at the frame-level energy-efficiently



QoS type: throughput

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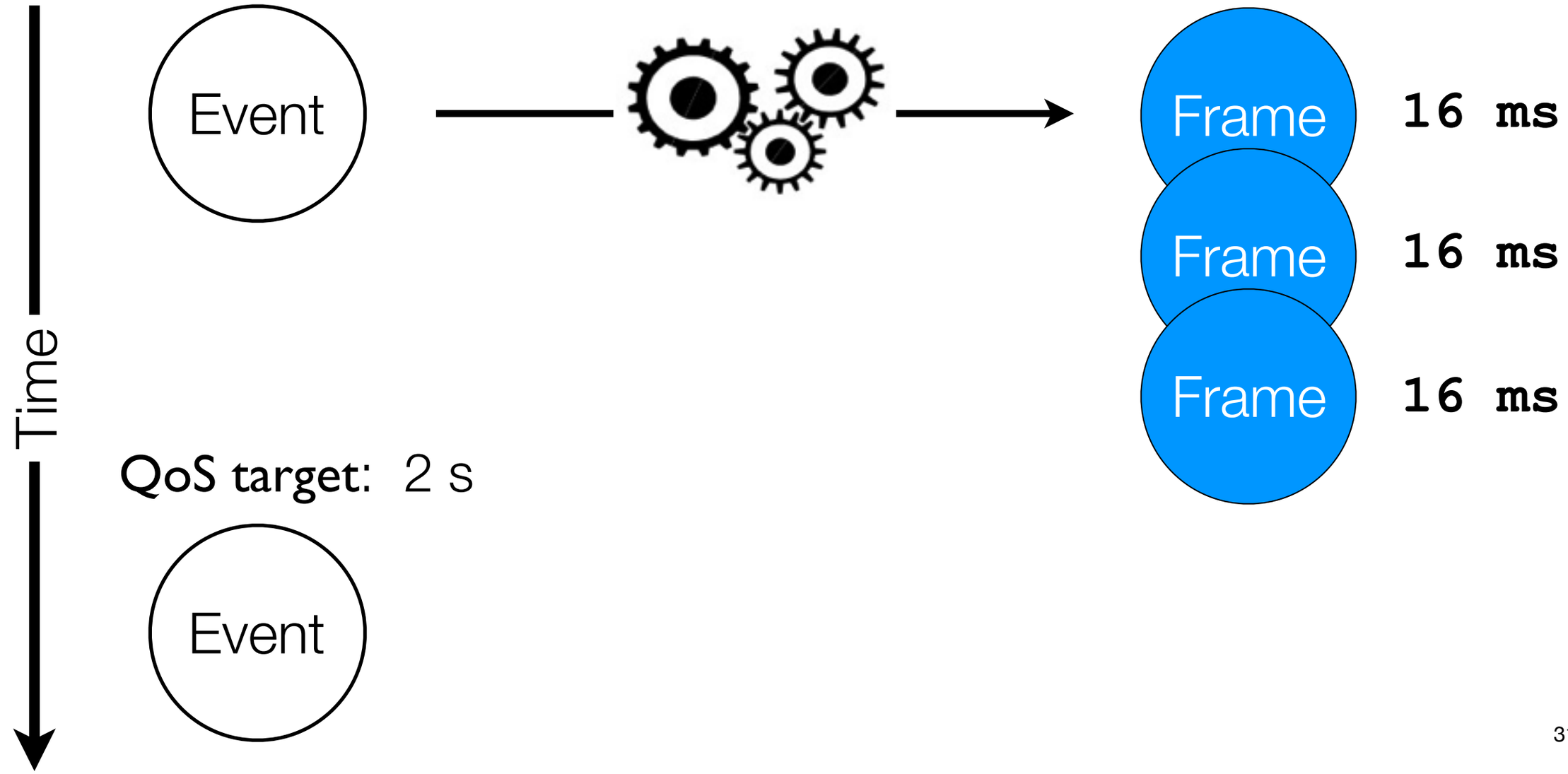
GreenWeb Runtime Overview

Runtime Objective

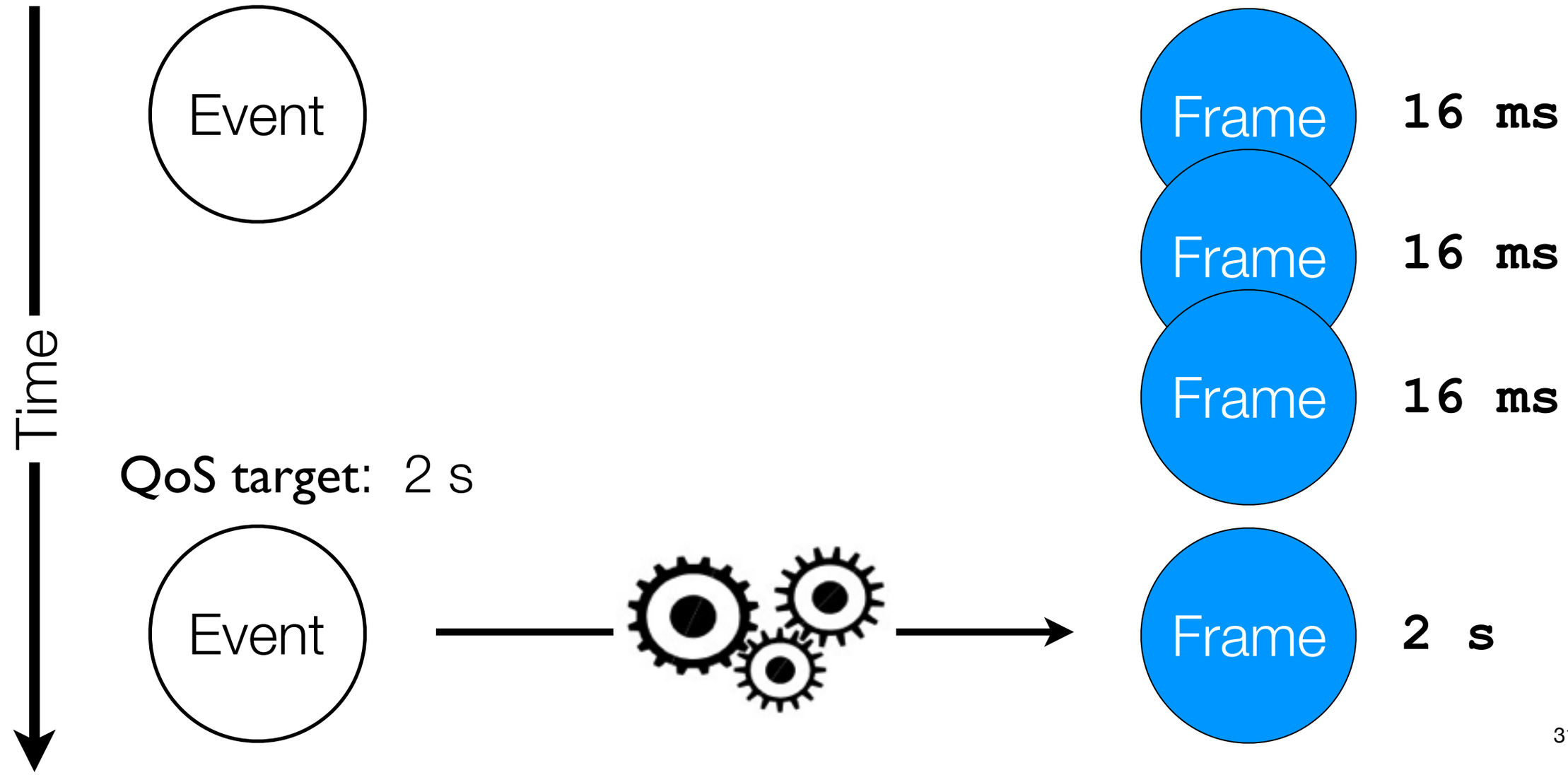
Enforcing event-level QoS at the frame-level energy-efficiently



GreenWeb Runtime Overview

Runtime Objective

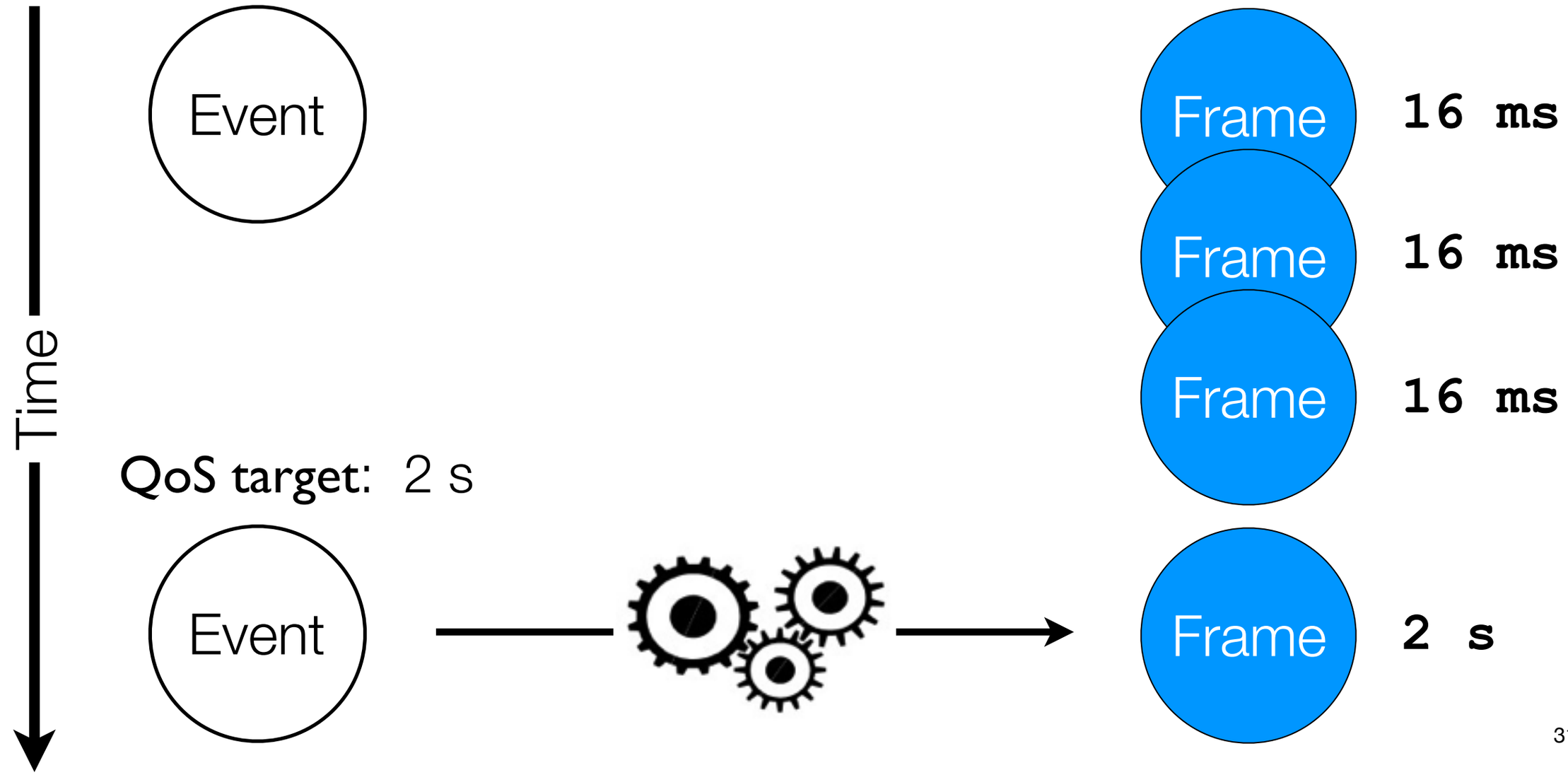
Enforcing event-level QoS at the frame-level energy-efficiently



GreenWeb Runtime Overview

Runtime Objective

Enforcing event-level QoS at the frame-level energy-efficiently {



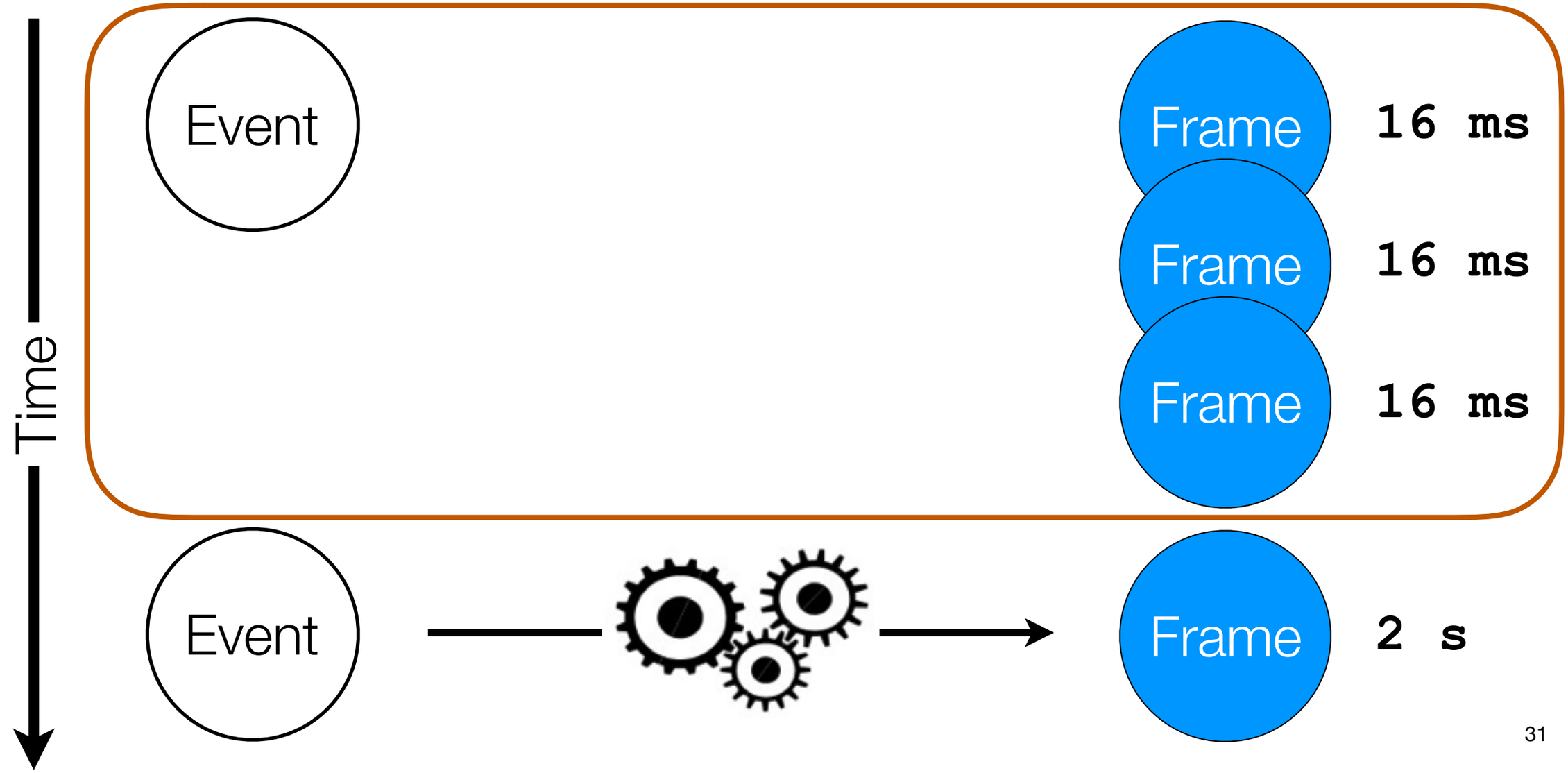
GreenWeb Runtime Overview

Runtime Objective

Enforcing event-level QoS at the frame-level energy-efficiently

{

1. Frame Association

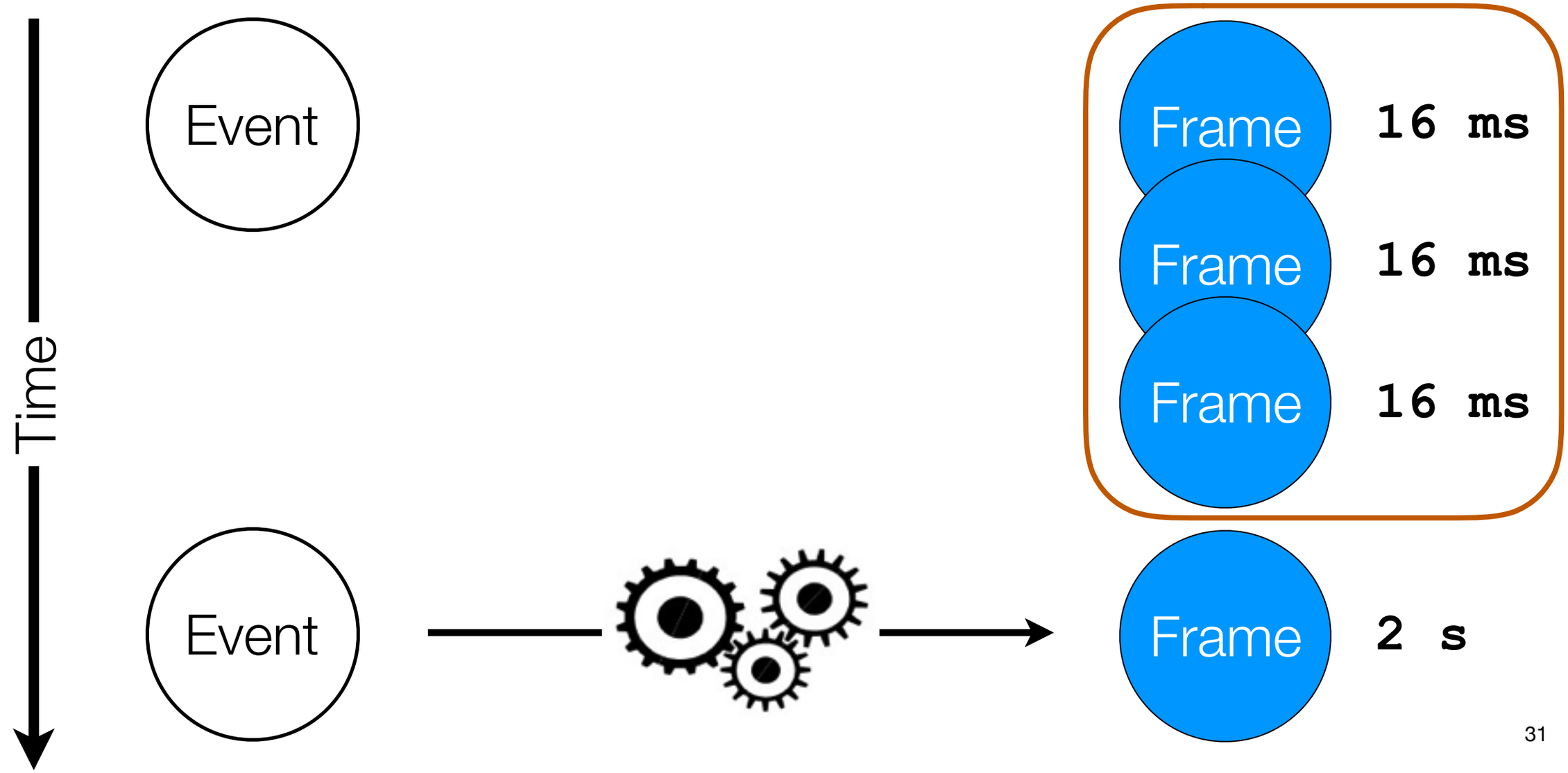


GreenWeb Runtime Overview

Runtime Objective

Enforcing event-level QoS at the frame-level energy-efficiently

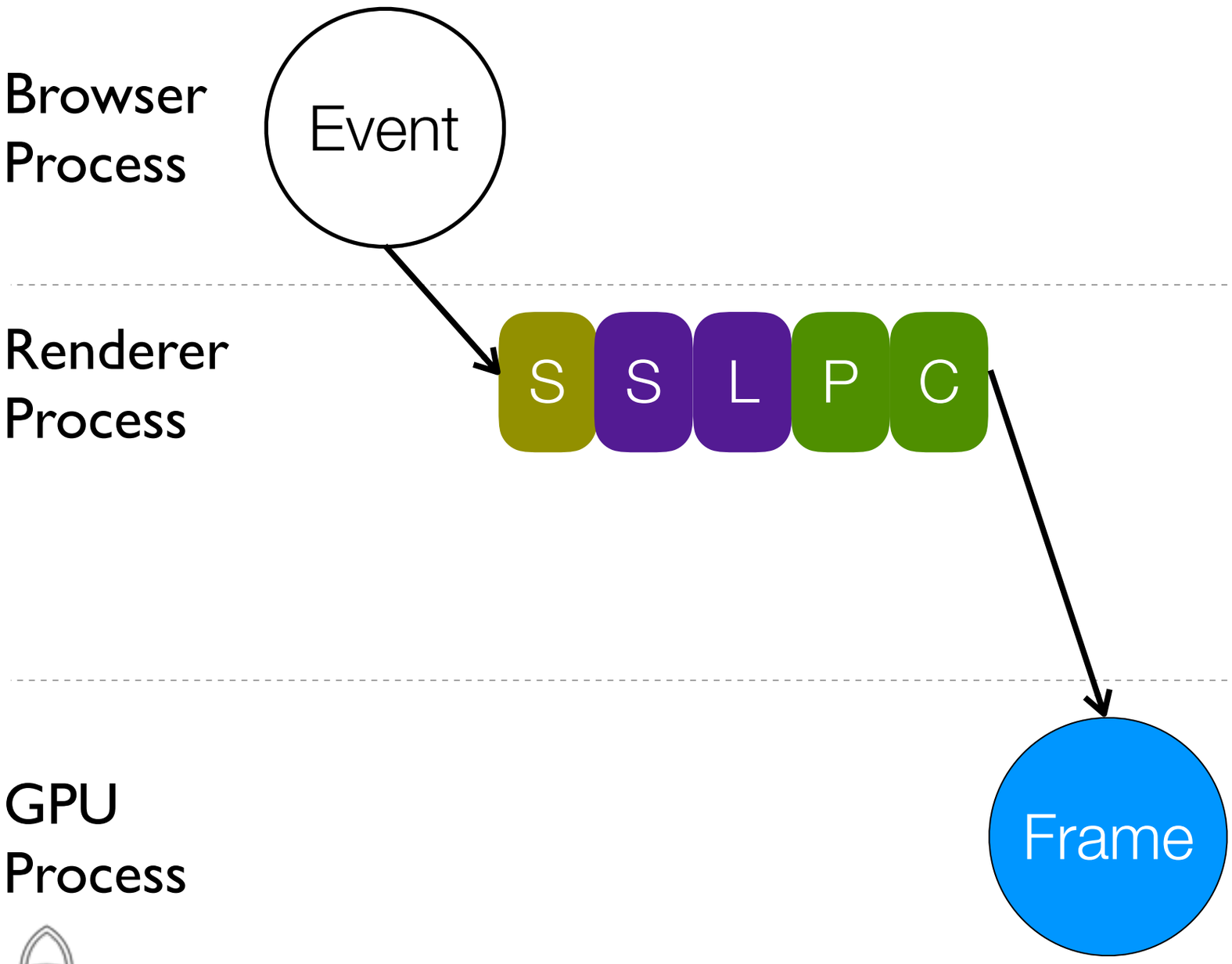
1. Frame Association
2. Frame Scheduling



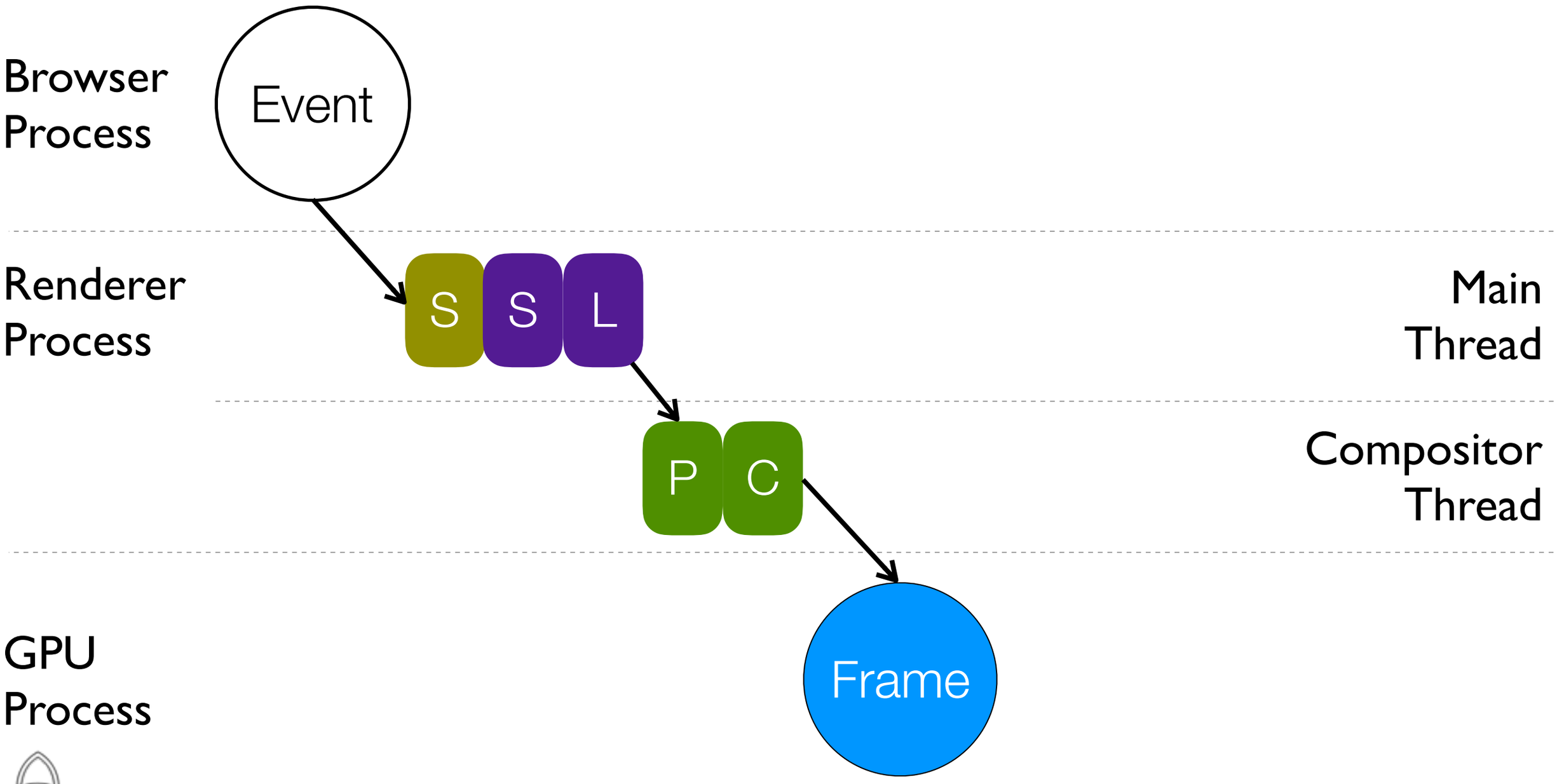
Frame Association

Frame Association

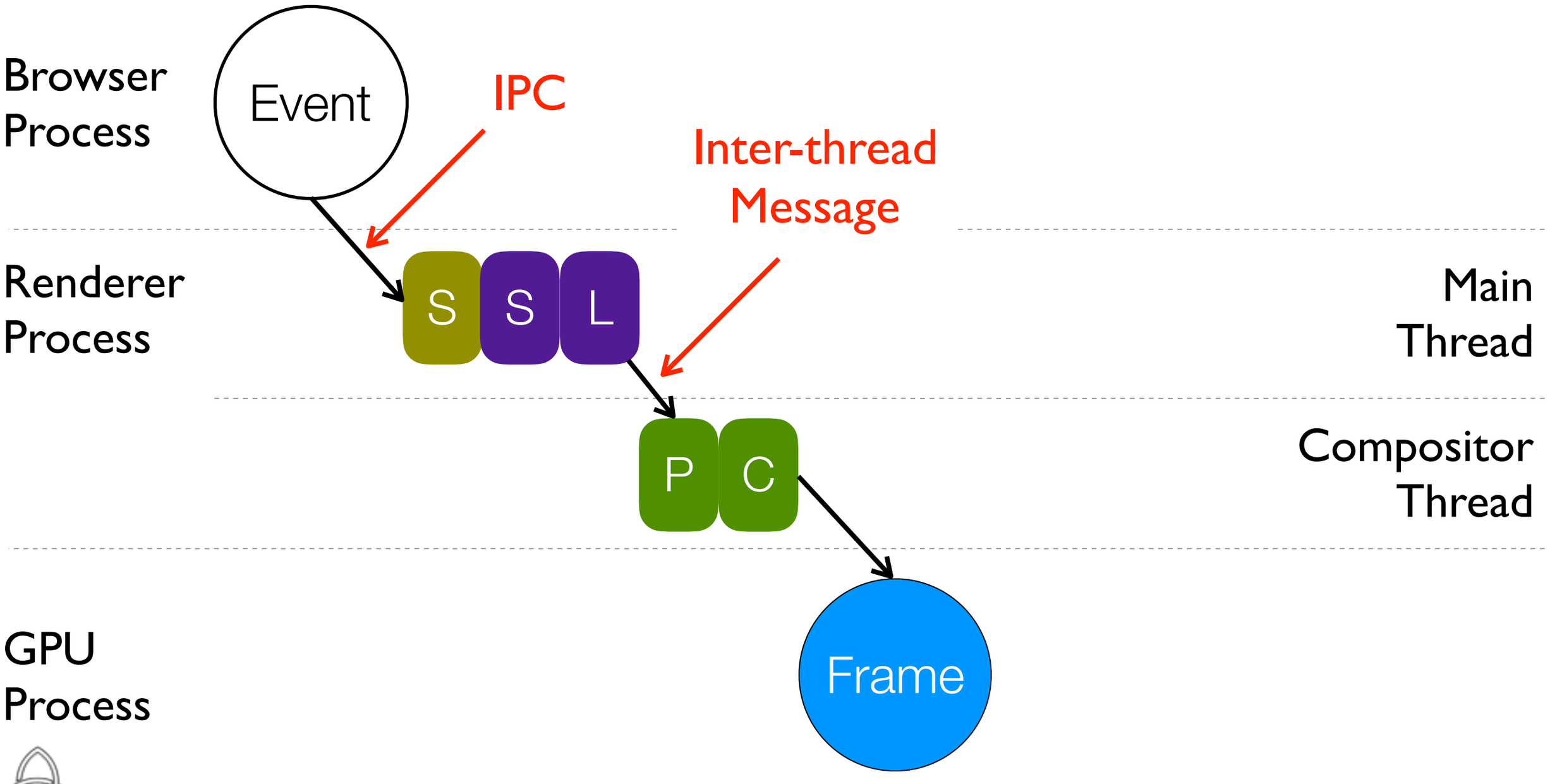
Frame Association



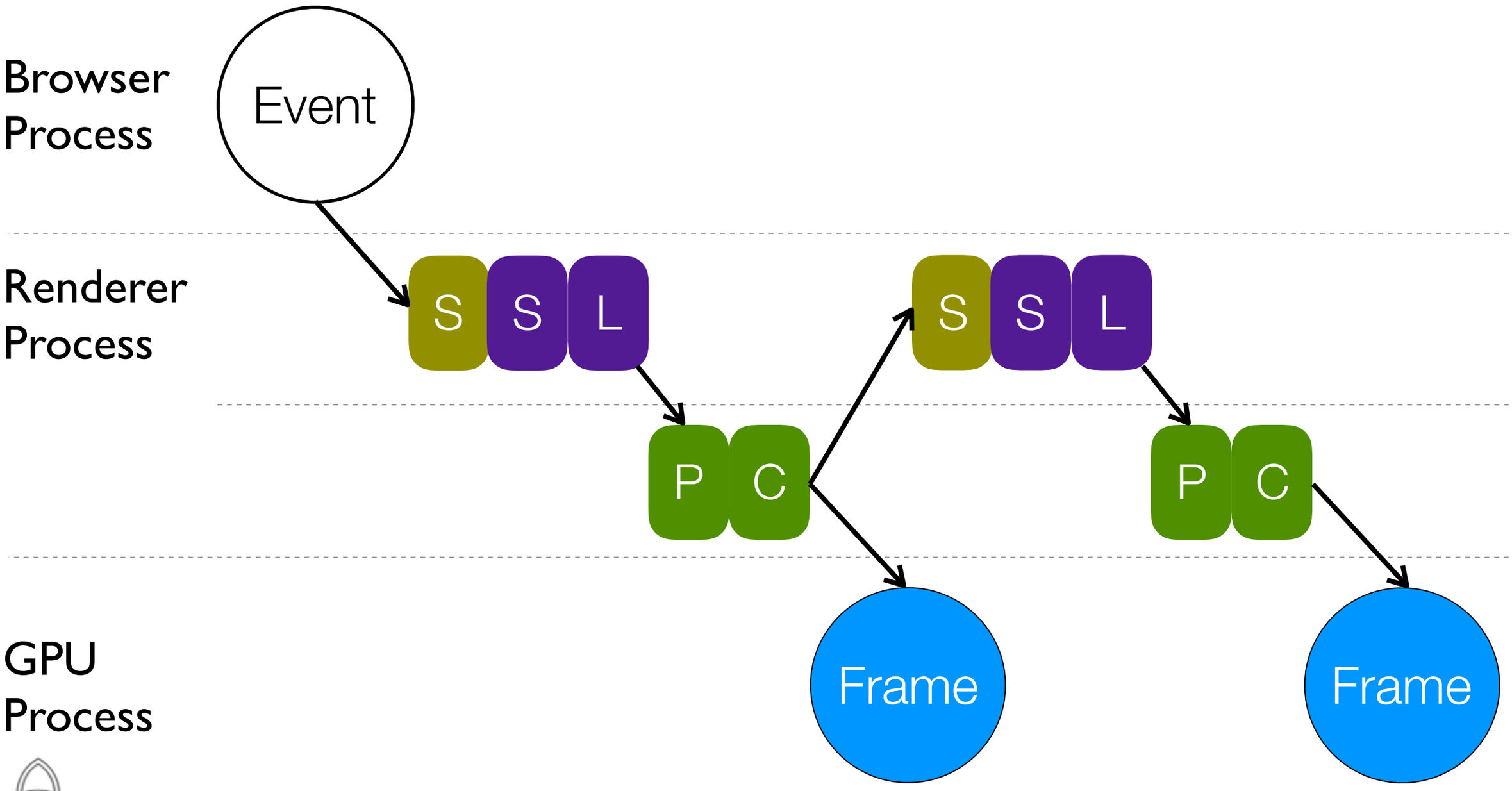
Frame Association



Frame Association

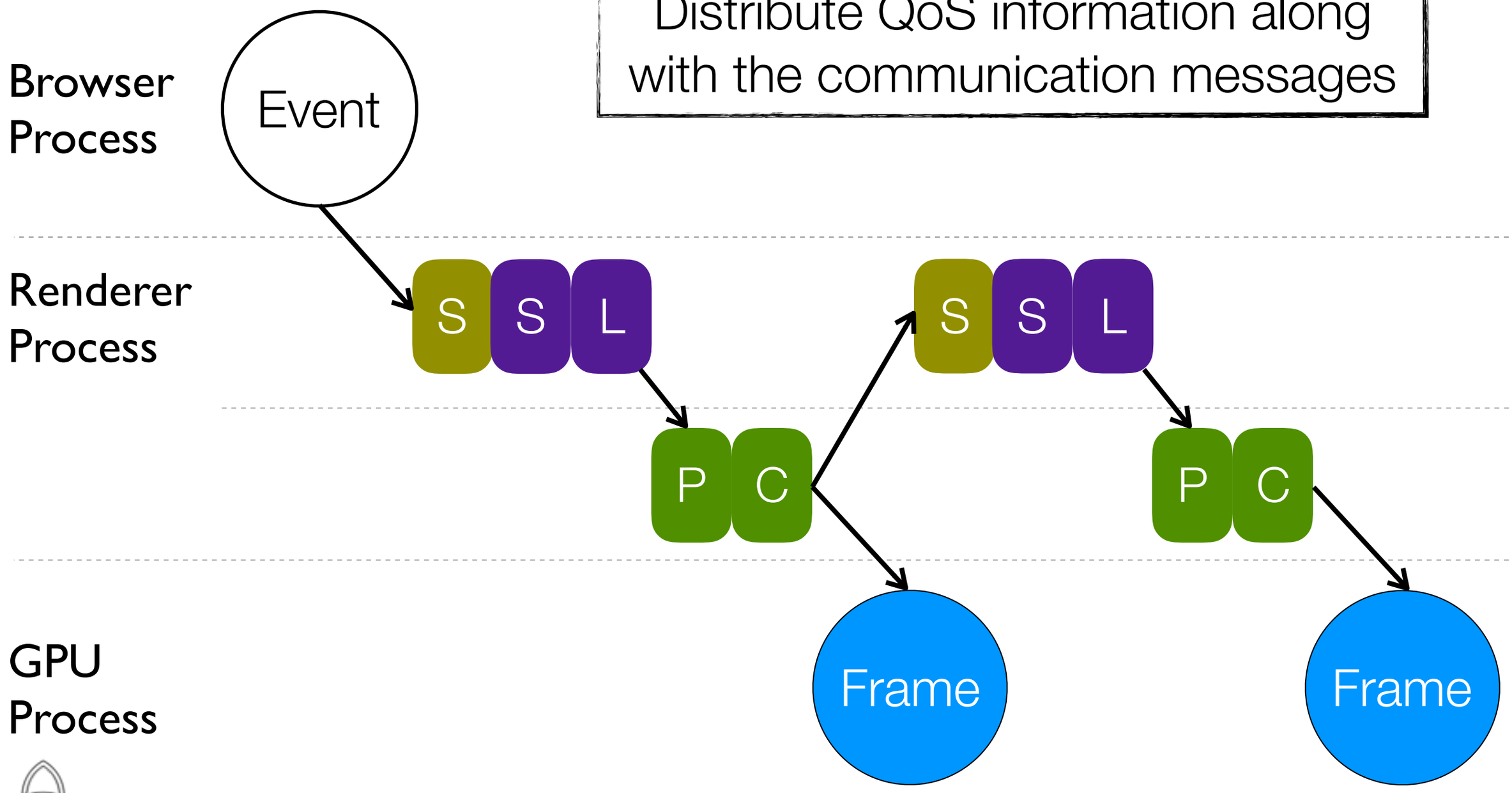


Frame Association



Frame Association

Distribute QoS information along with the communication messages



Choices of Energy-saving Techniques

GreenWeb can support a range of energy saving techniques

Choices of Energy-saving Techniques

GreenWeb can support a range of energy saving techniques

- Dynamic resolution scaling [MobiCom 2015]
- Power-saving display colors [MobiSys 2012]
- Selective resource loading [NSDI 2015]

Choices of Energy-saving Techniques

GreenWeb can support a range of energy saving techniques

- Dynamic resolution scaling [MobiCom 2015]
- Power-saving display colors [MobiSys 2012]
- Selective resource loading [NSDI 2015]
- ACMP-based hardware mechanism (WebRT)

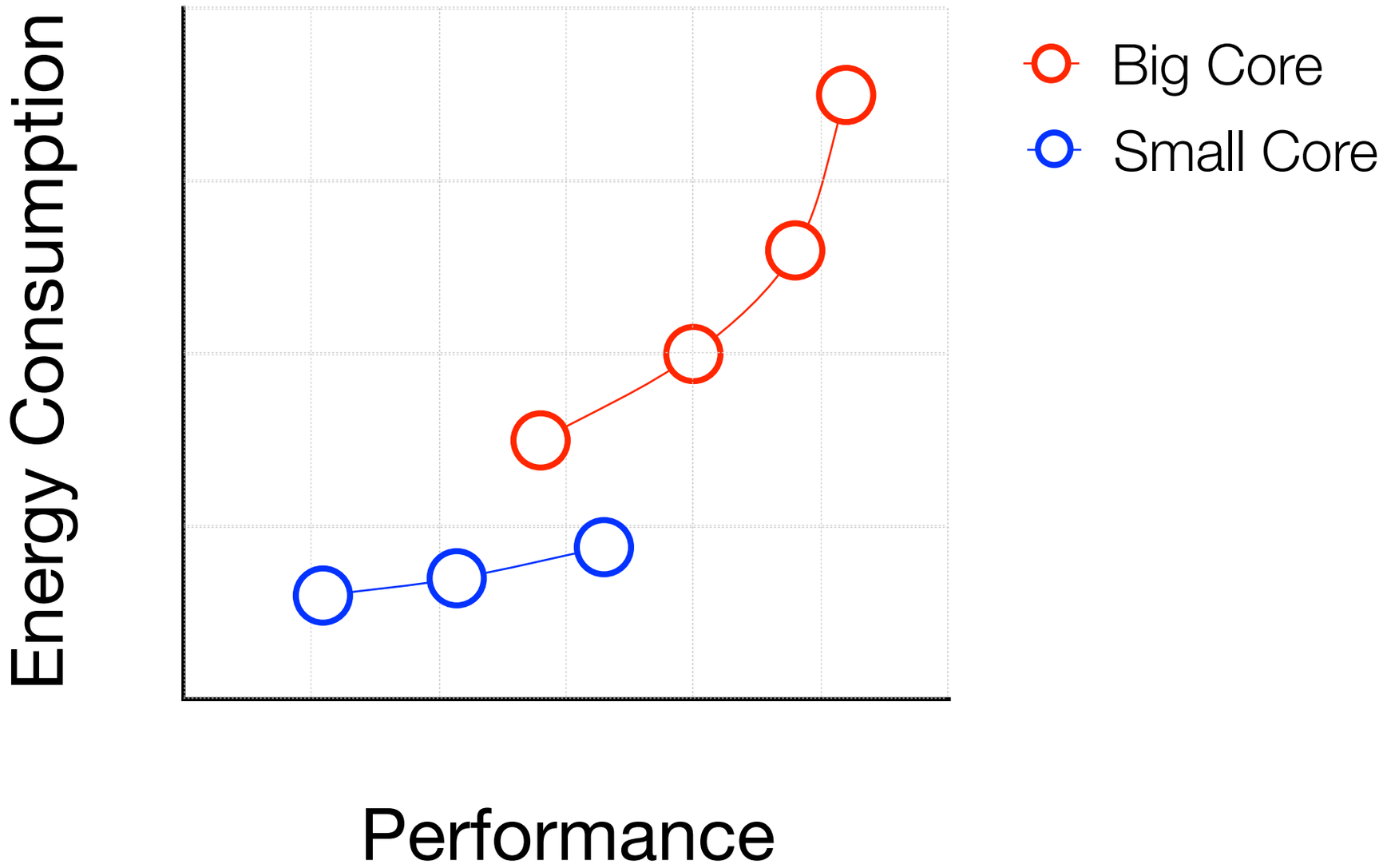
Asymmetric Chip-multiprocessor

Asymmetric Chip-multiprocessor

- Offer a large performance-energy trade-off space

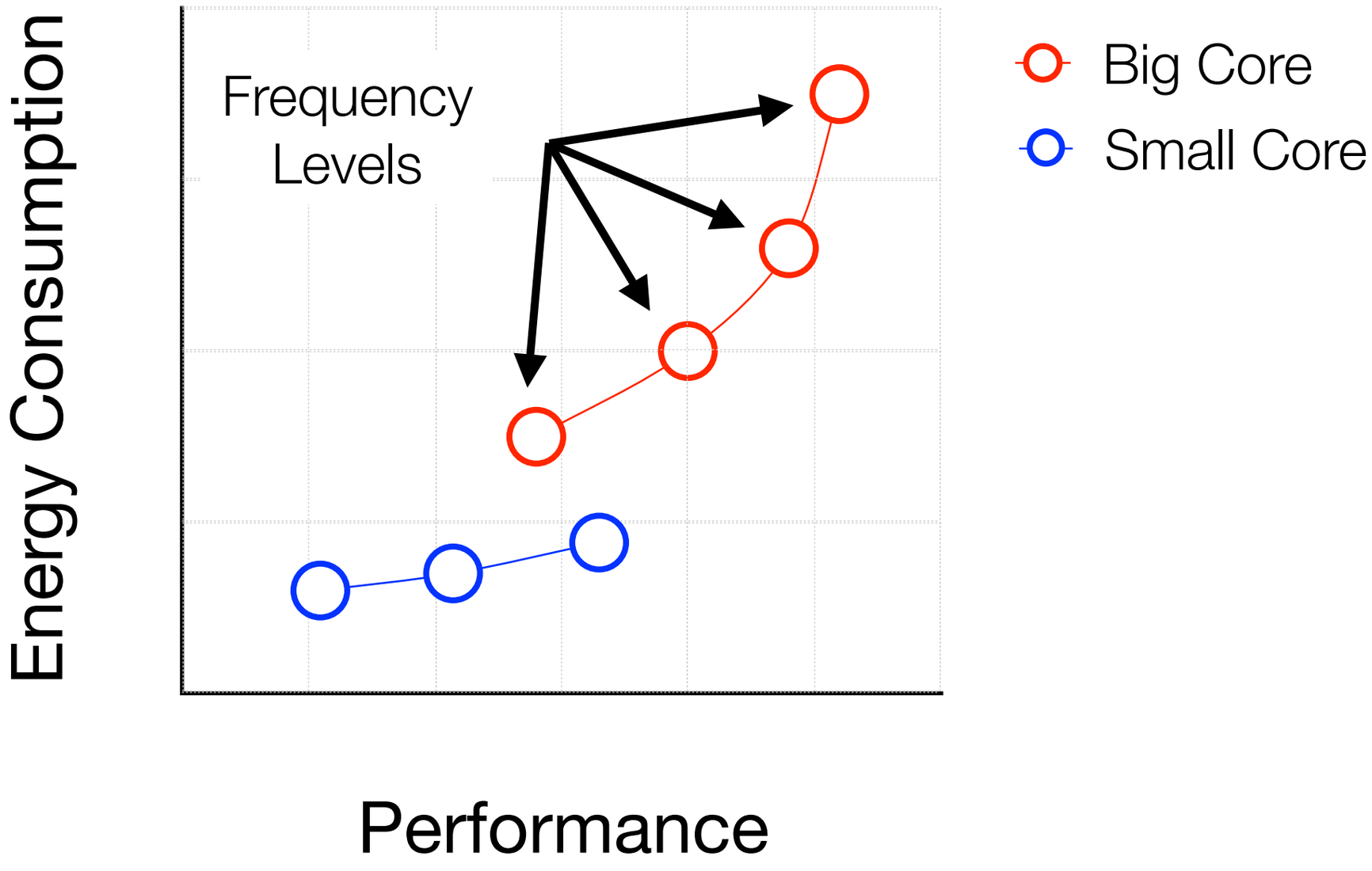
Asymmetric Chip-multiprocessor

- Offer a large performance-energy trade-off space



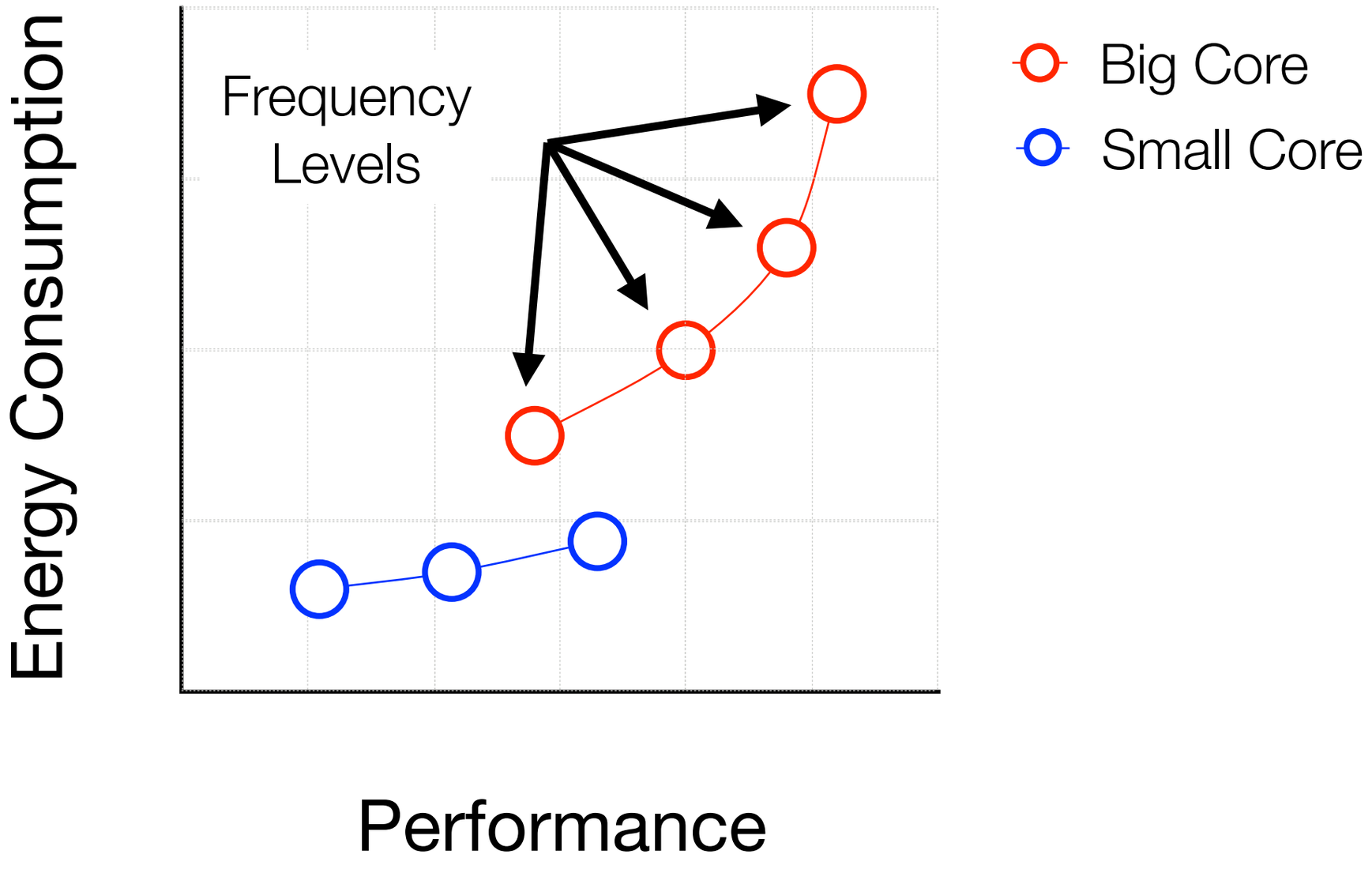
Asymmetric Chip-multiprocessor

- Offer a large performance-energy trade-off space



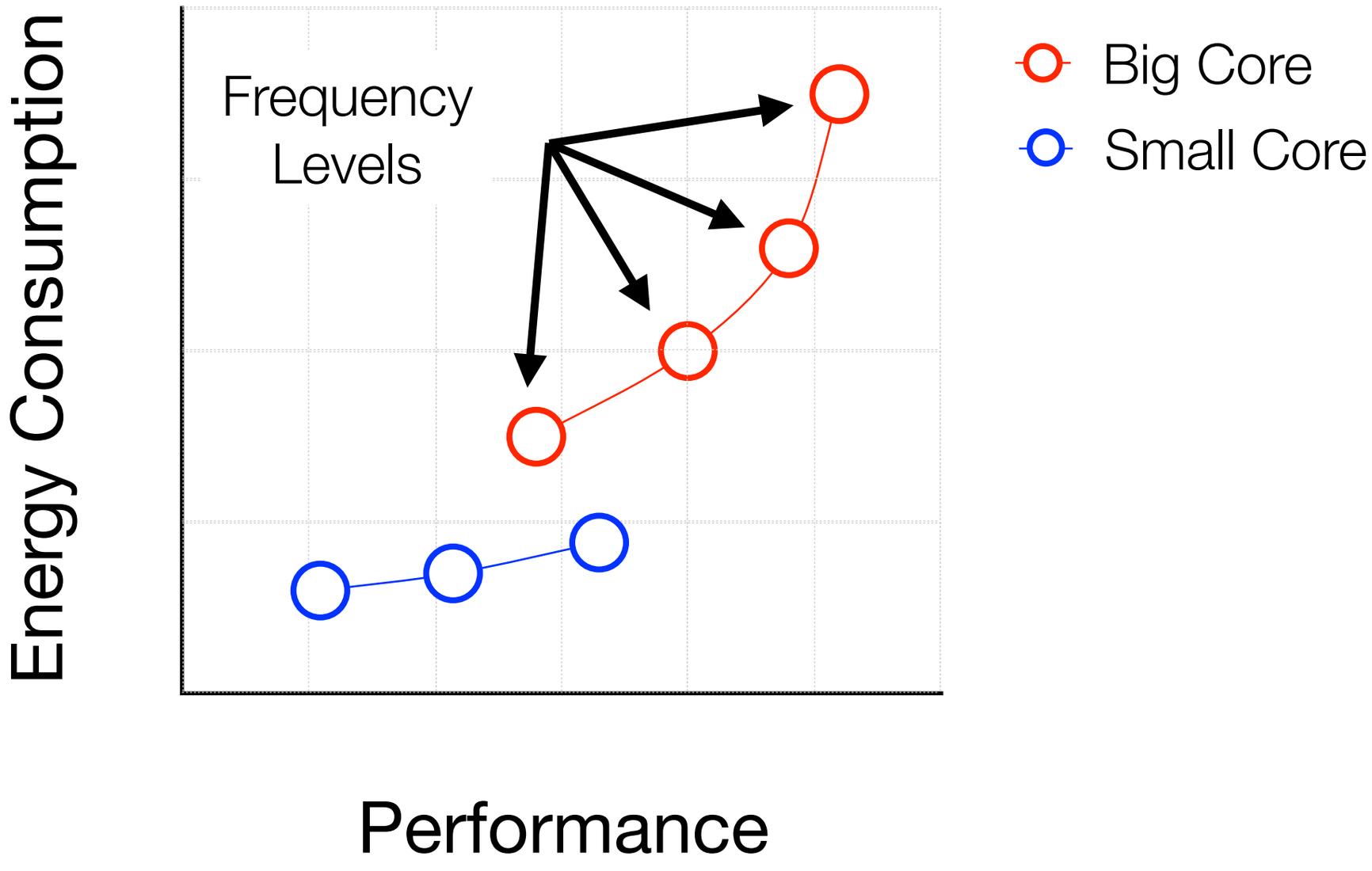
Asymmetric Chip-multiprocessor

- Offer a large performance-energy trade-off space
- Already used in commodity devices (e.g., Samsung Galaxy S6)



ACMP-based **GreenWeb** Runtime

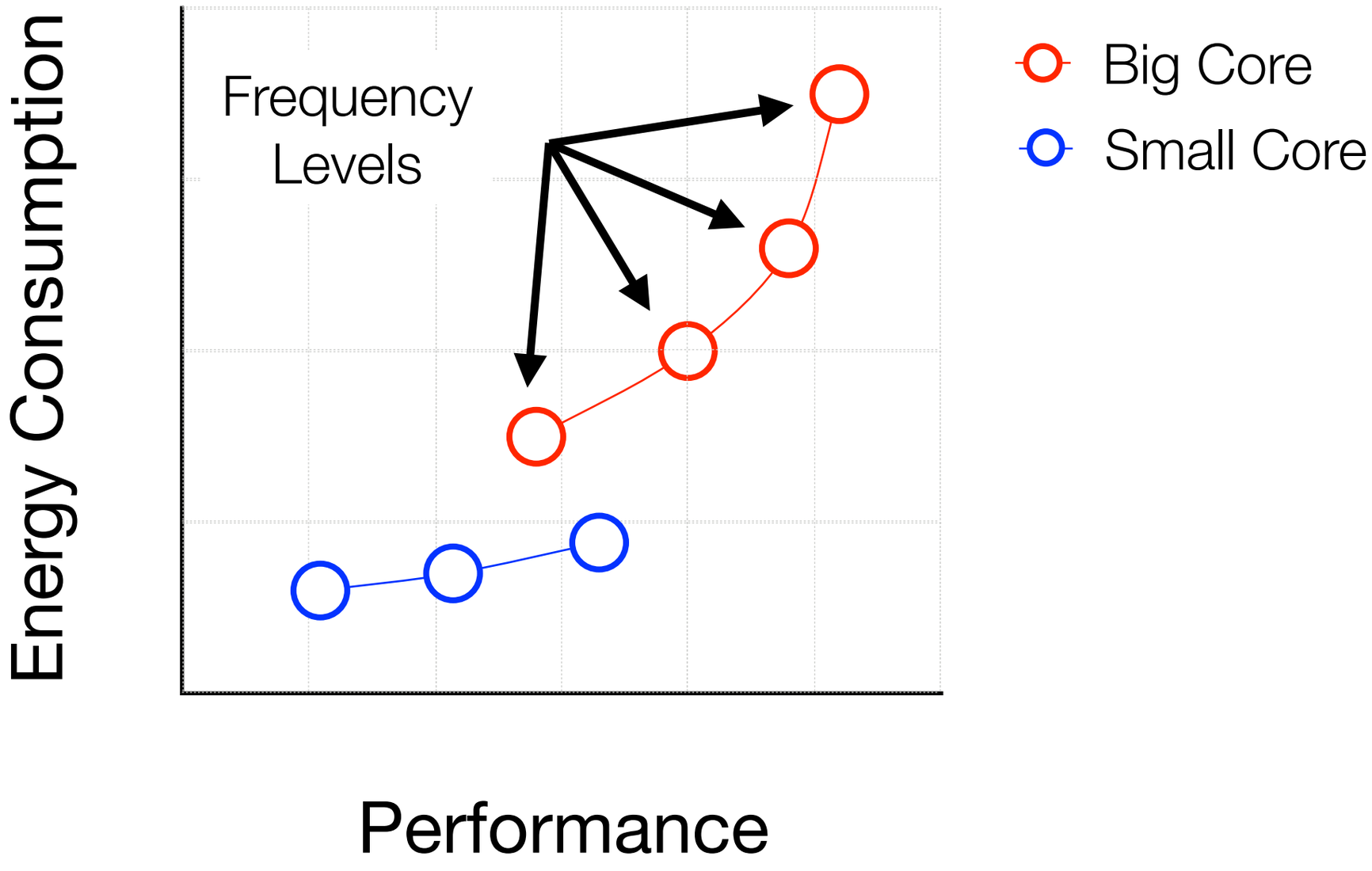
- Provide just enough energy to meet QoS constraints



ACMP-based **GreenWeb** Runtime

- Provide just enough energy to meet QoS constraints

```
div {ontouchend: latency, 16 ms}
```



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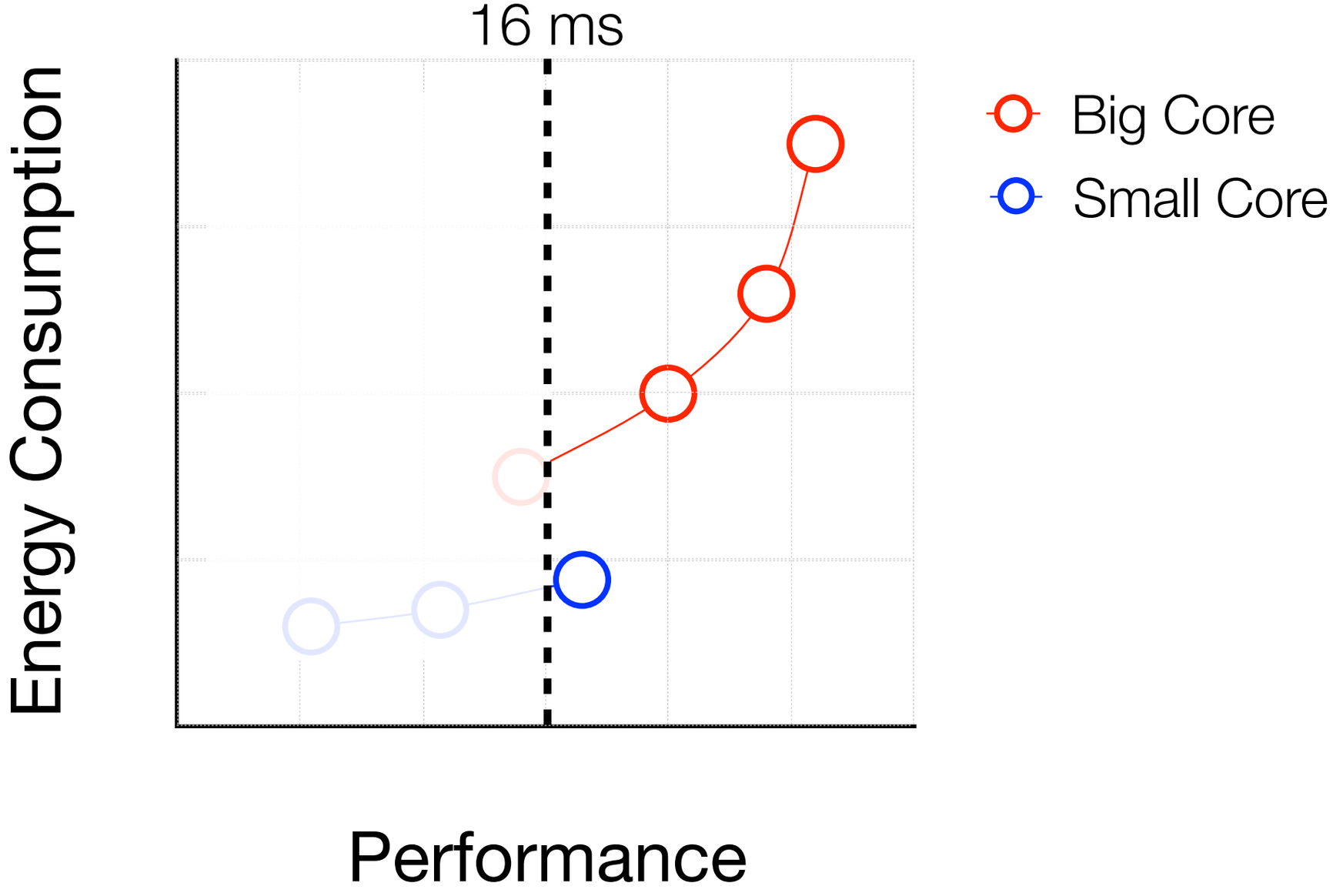

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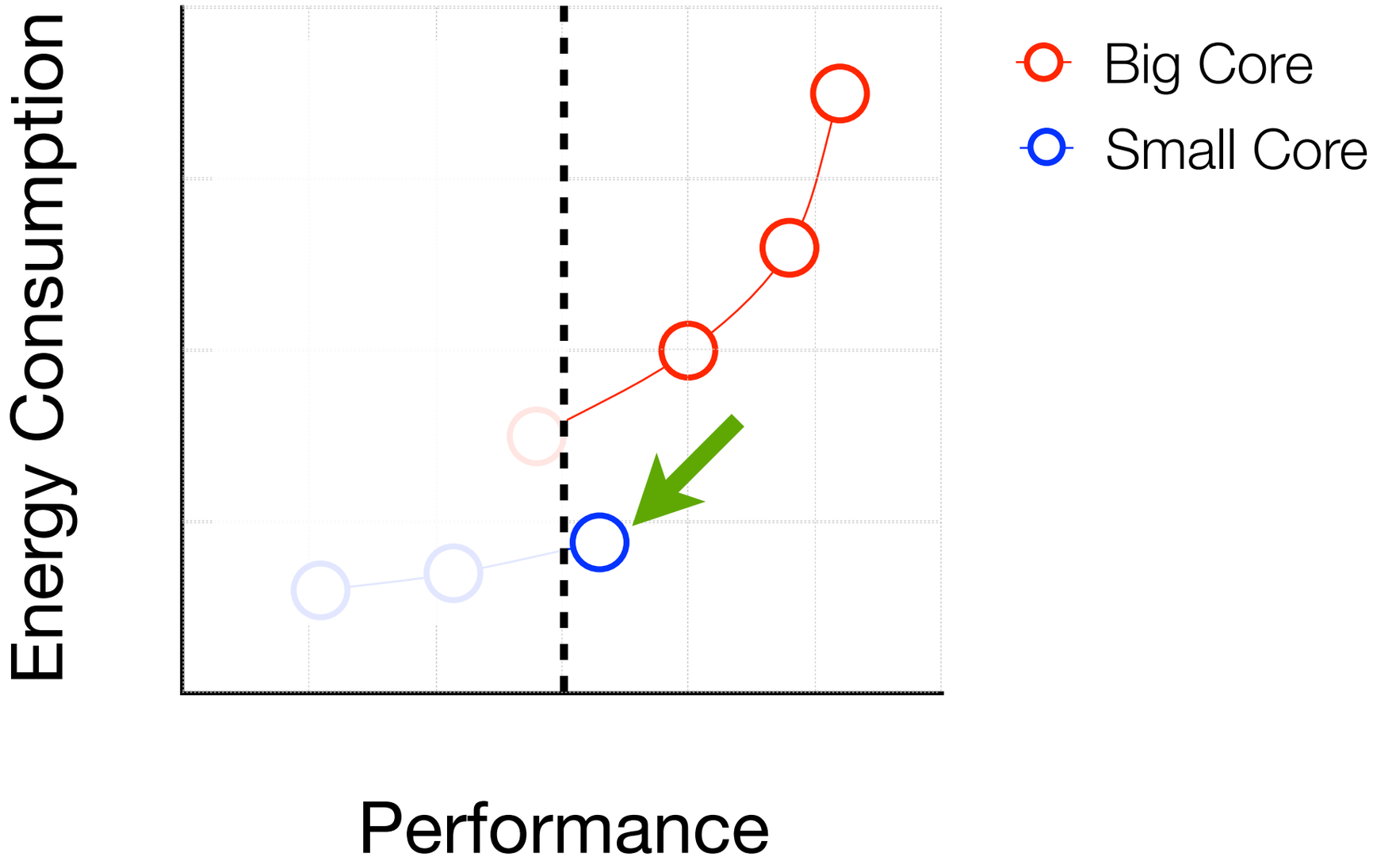

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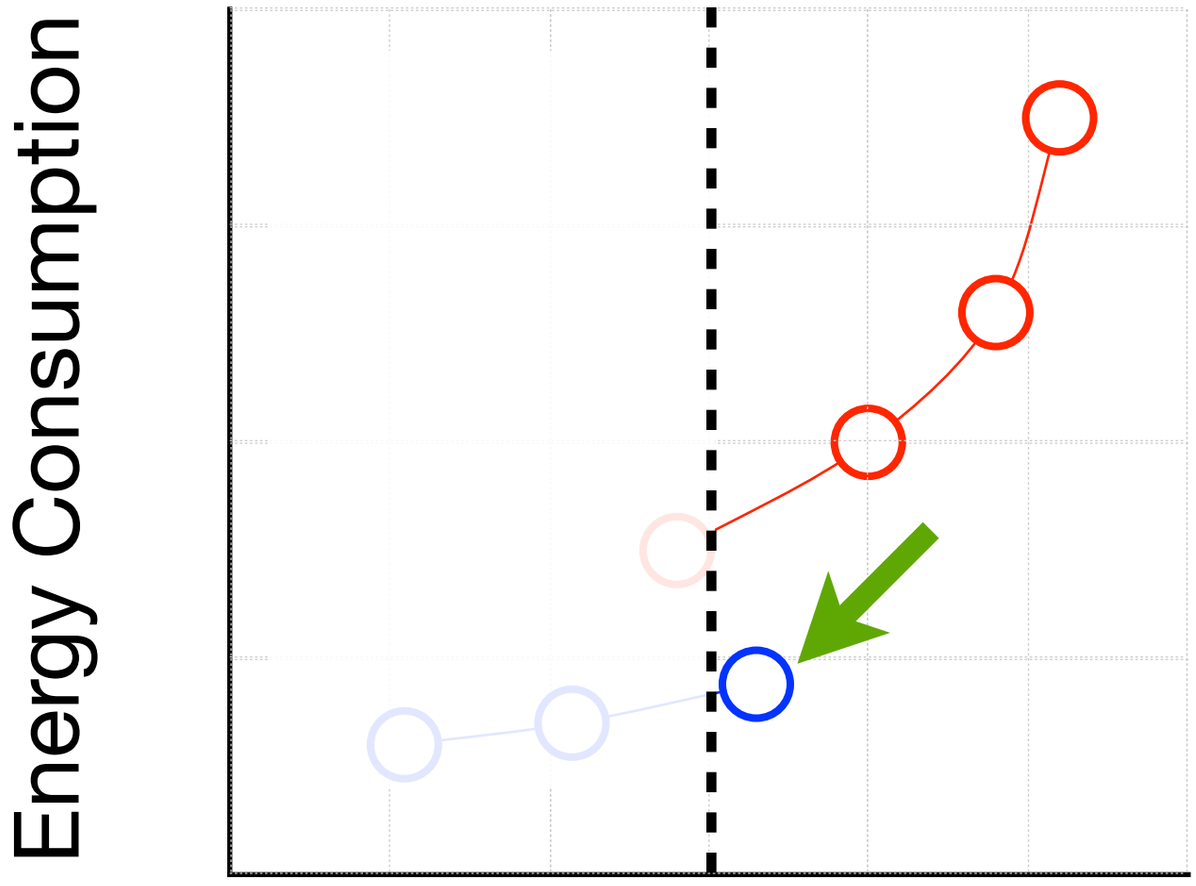
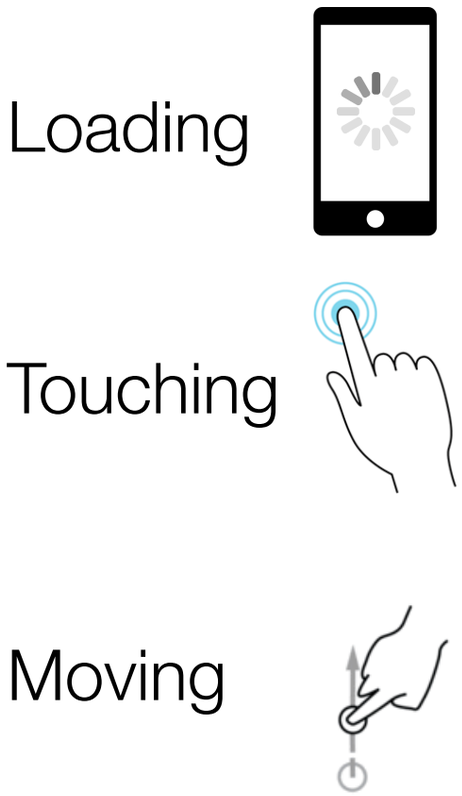
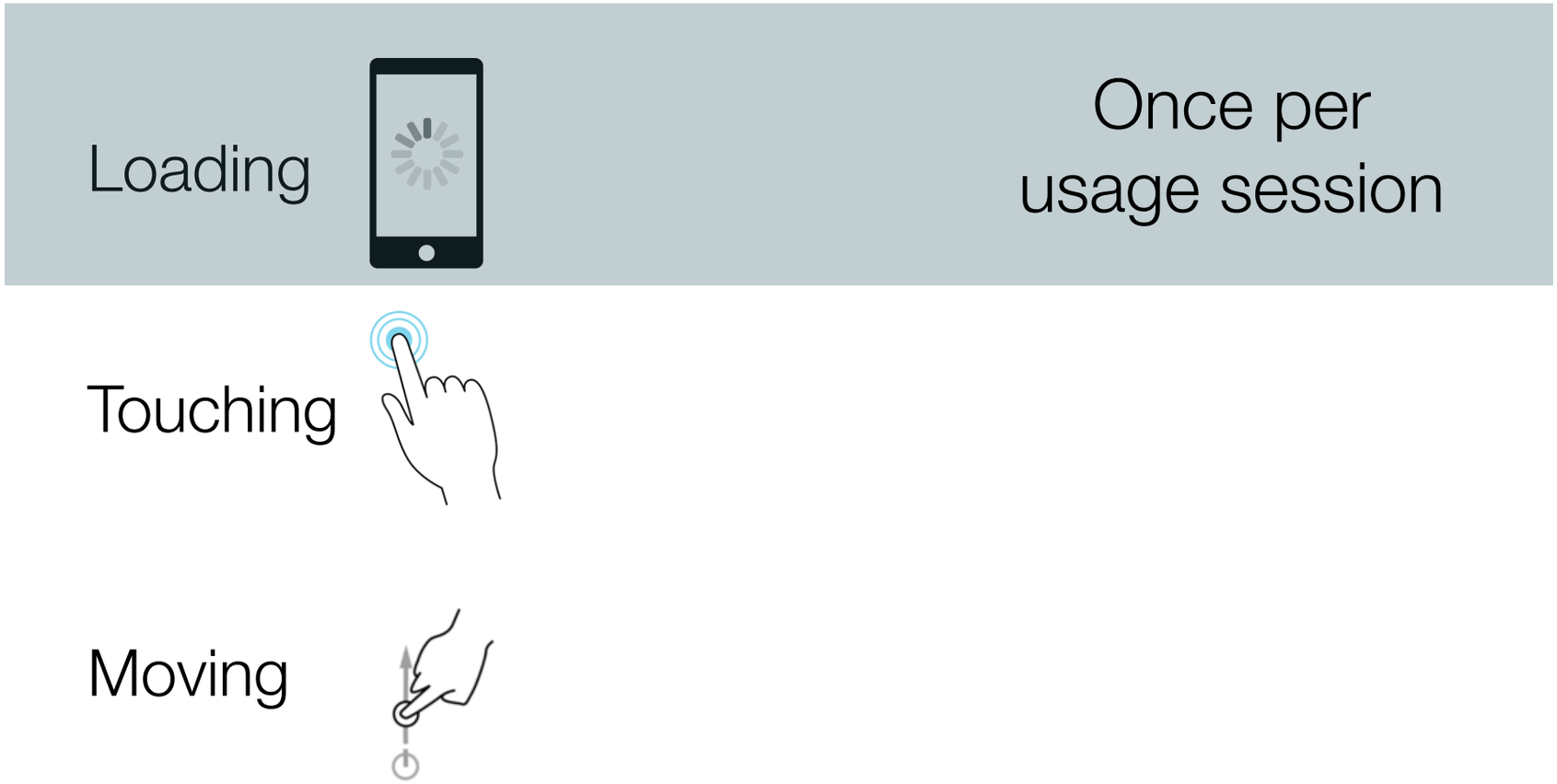


Predict the performance and energy of each configuration!

Different Strategies for Different Events



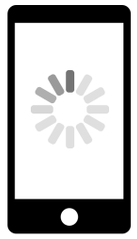
Different Strategies for Different Events



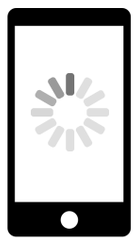
Different Strategies for Different Events

Events	WebRT Component
Loading 	Proactive Mechanism
Touching 	
Moving 	

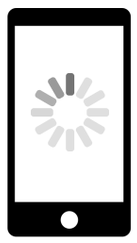
Different Strategies for Different Events

Events	WebRT Component
Loading 	Proactive Mechanism
Touching 	Repetitive in a usage session
Moving 	

Different Strategies for Different Events

Events	WebRT Component
Loading 	Proactive Mechanism
Touching 	Adaptive Mechanism
Moving 	

Different Strategies for Different Events

Events	WebRT Component
Loading 	Proactive Mechanism
Touching	Adaptive Mechanism
Moving	

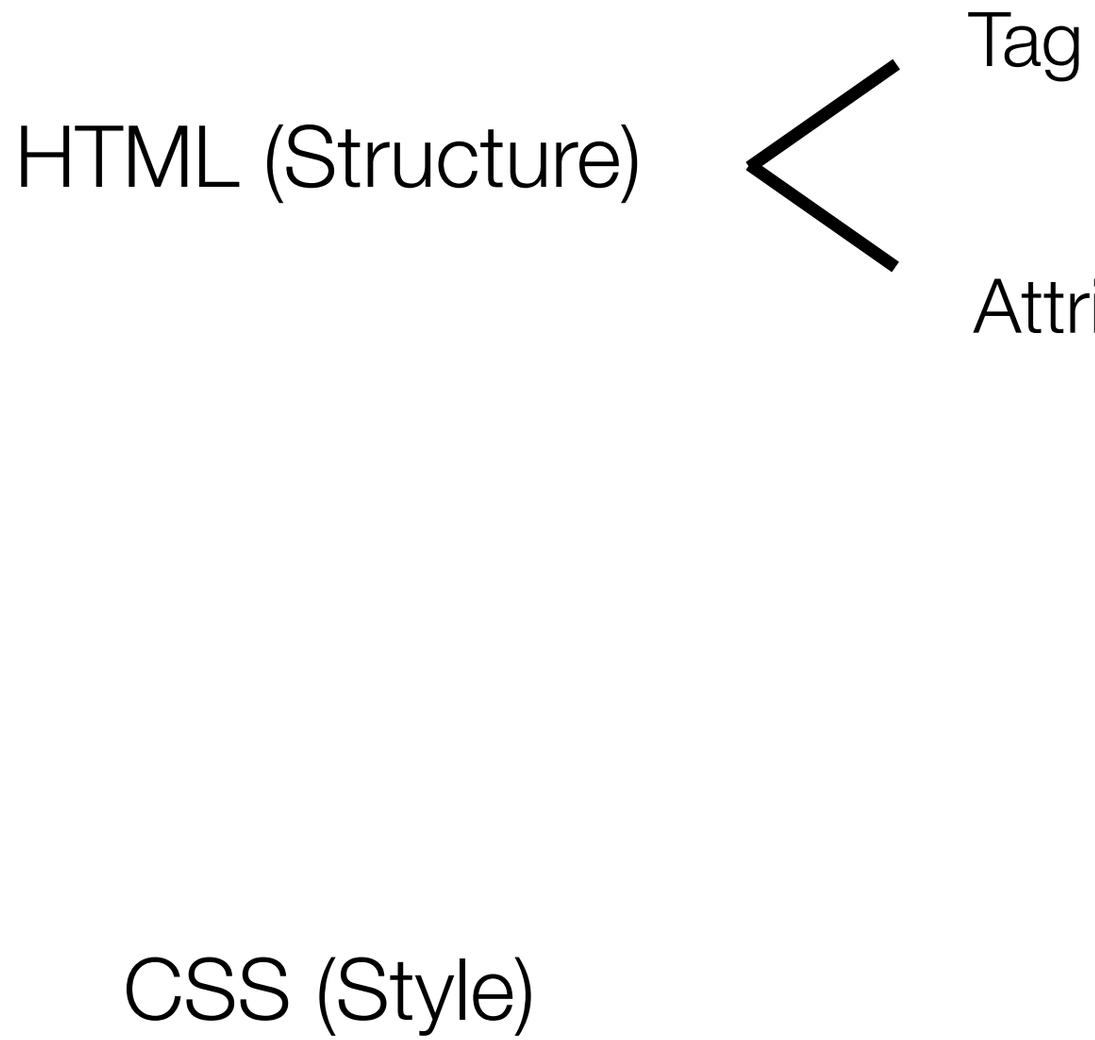
Breaking Down the Computations

Breaking Down the Computations

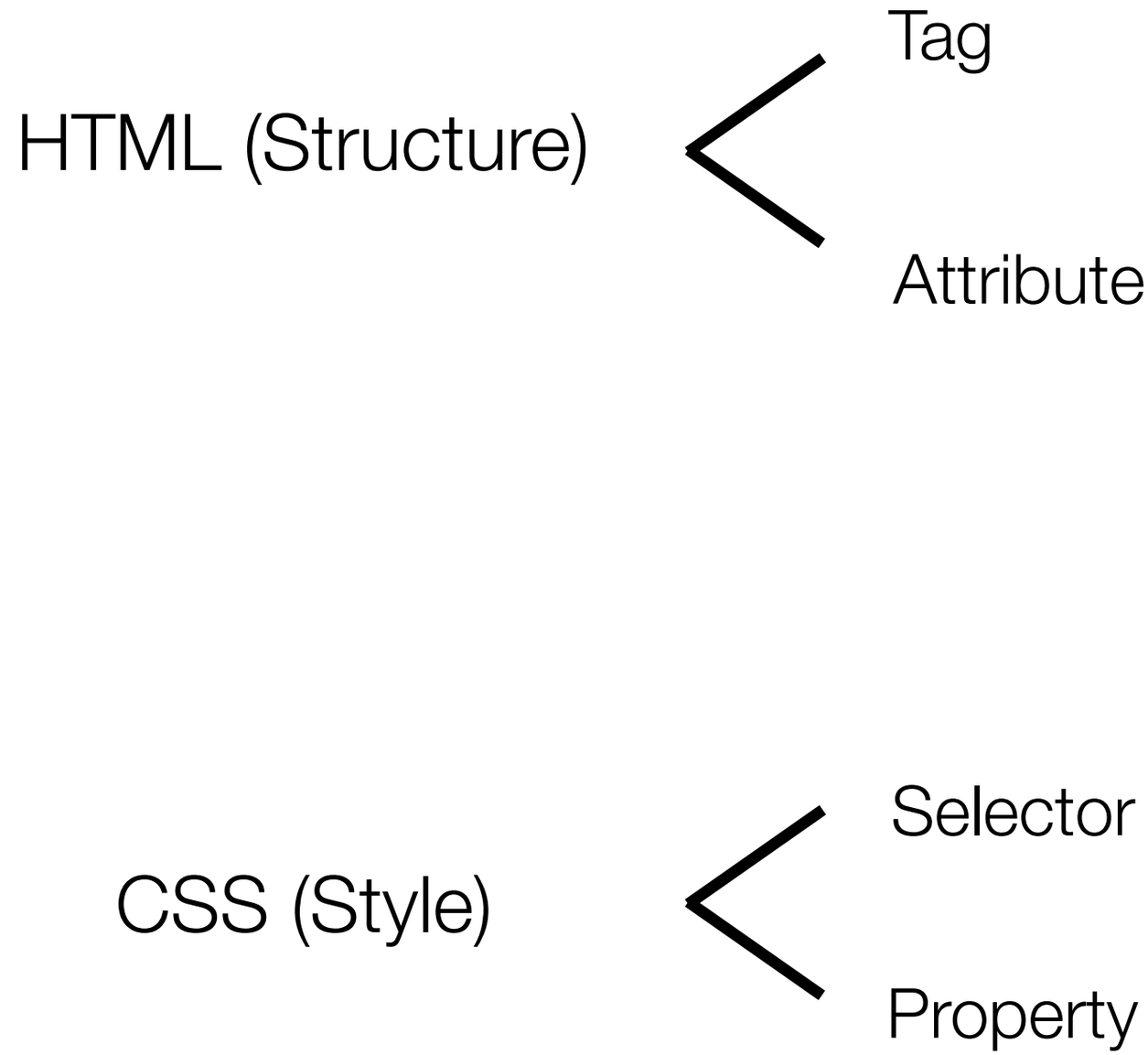
HTML (Structure)

CSS (Style)

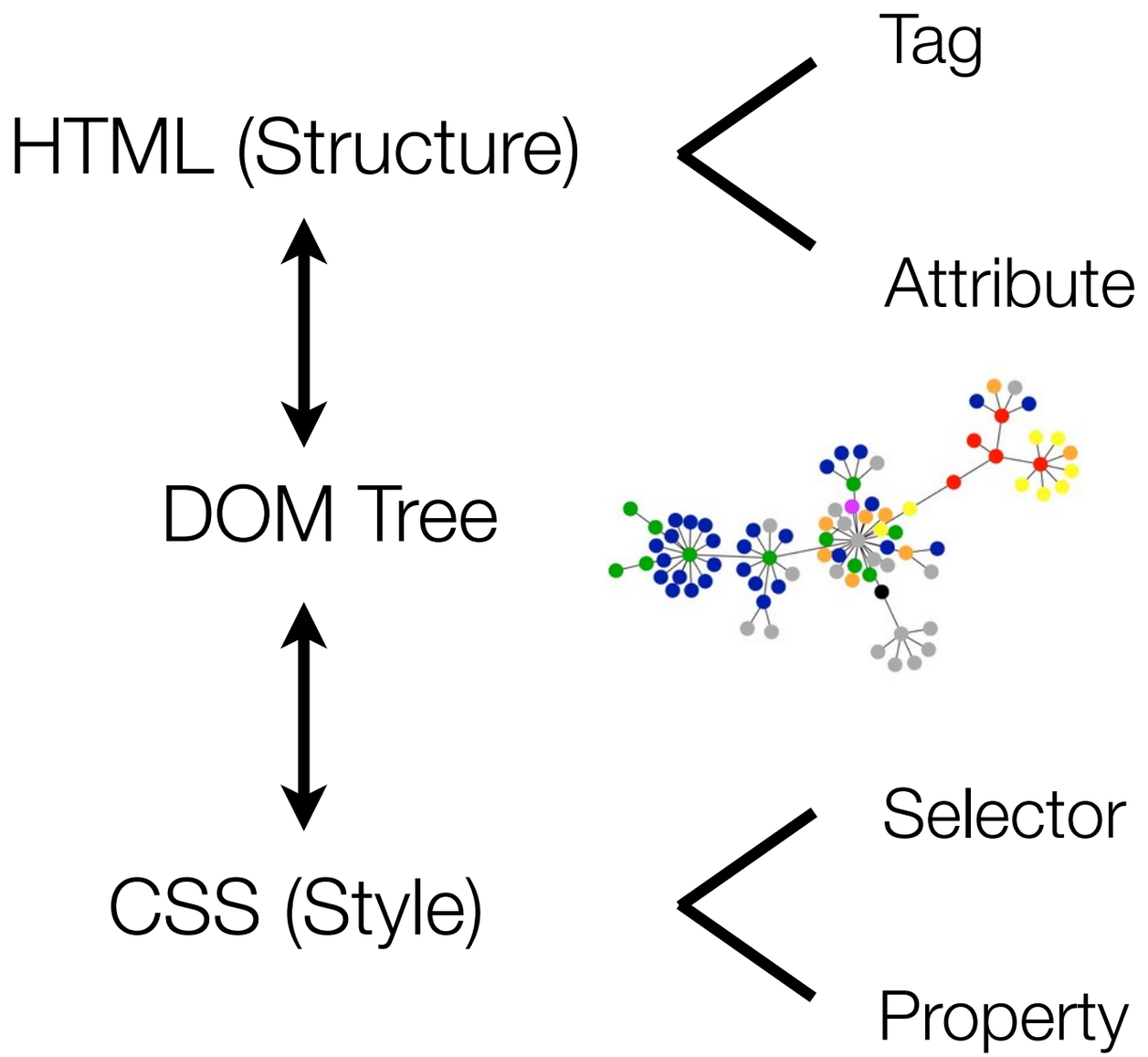
Breaking Down the Computations



Breaking Down the Computations



Breaking Down the Computations



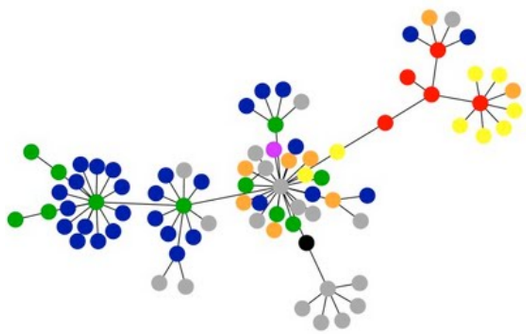
Breaking Down the Computations

Web Primitives

HTML (Structure)

Tag

Attribute



DOM Tree

CSS (Style)

Selector

Property

Predicting Loading Performance & Energy

Idea: predict load time & energy (responses)
based on Web primitives (predictors)

Predicting Loading Performance & Energy

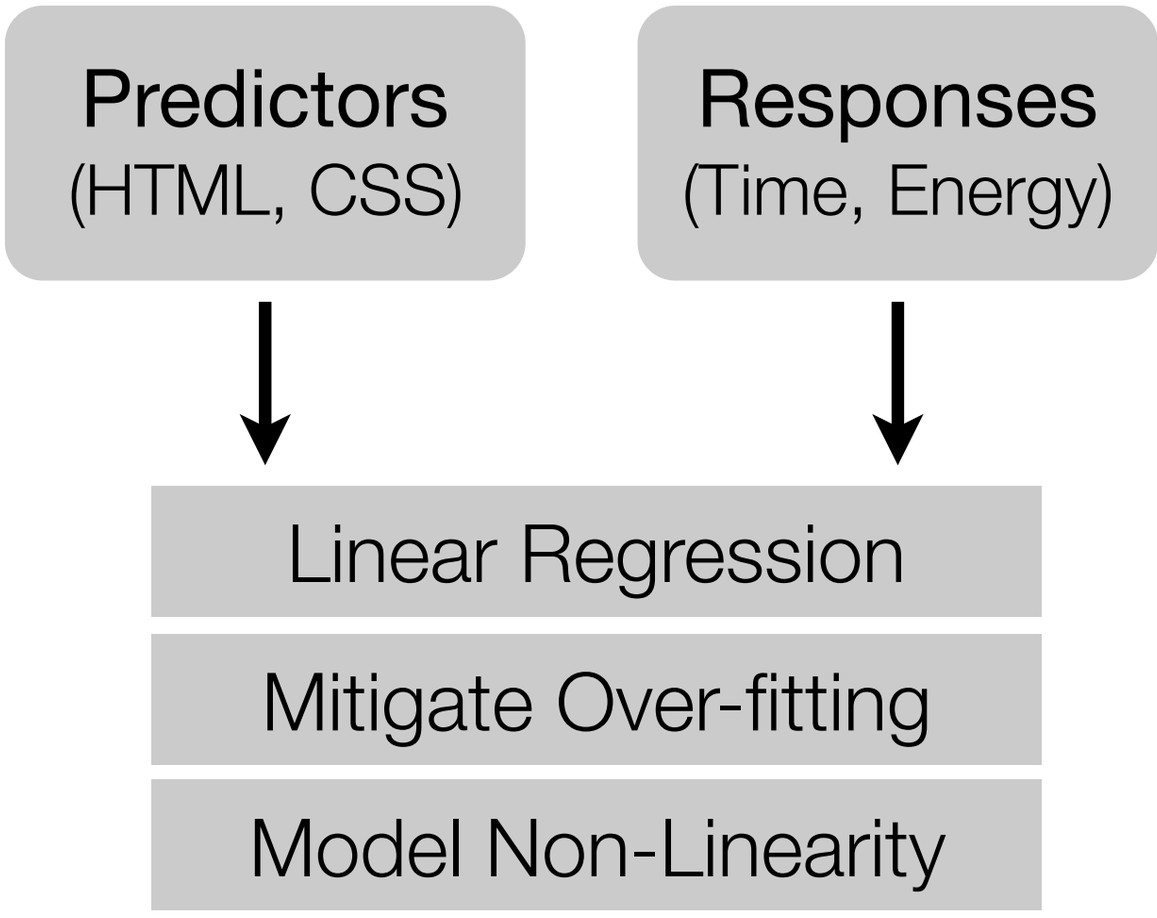
Identify Predictors
Training using top
2,500 webpages

Predictors
(HTML, CSS)

Responses
(Time, Energy)

Predicting Loading Performance & Energy

Identify Predictors
Training using top 2,500 webpages



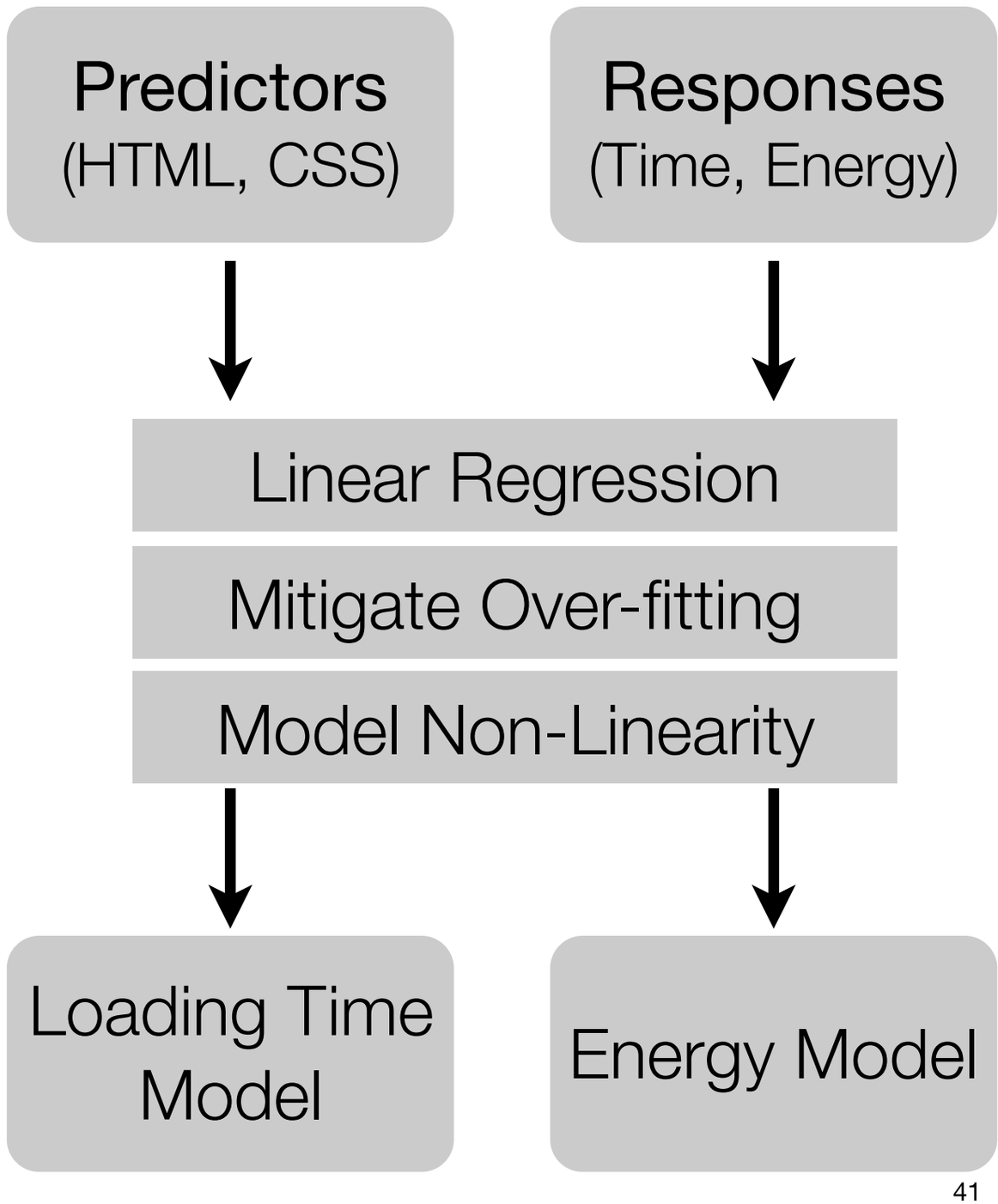
Model Construction & Refinement
Refine the linear model

Predicting Loading Performance & Energy

Identify Predictors
Training using top 2,500 webpages

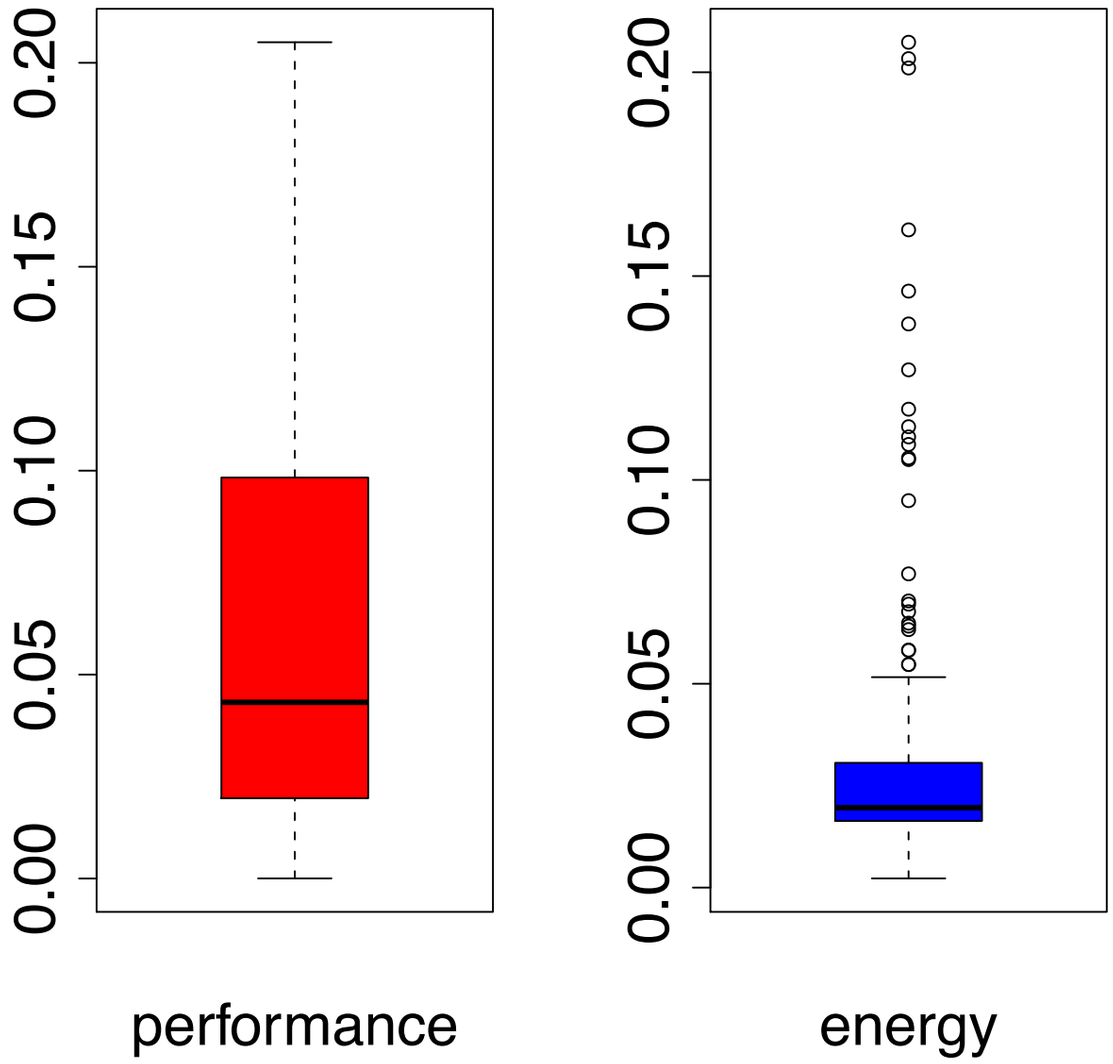
Model Construction & Refinement
Refine the linear model

Model Validation
Validating on another 2,500 webpages

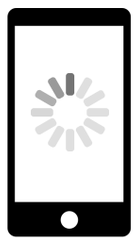


Predicting Loading Performance & Energy

Median prediction error is less than 5%



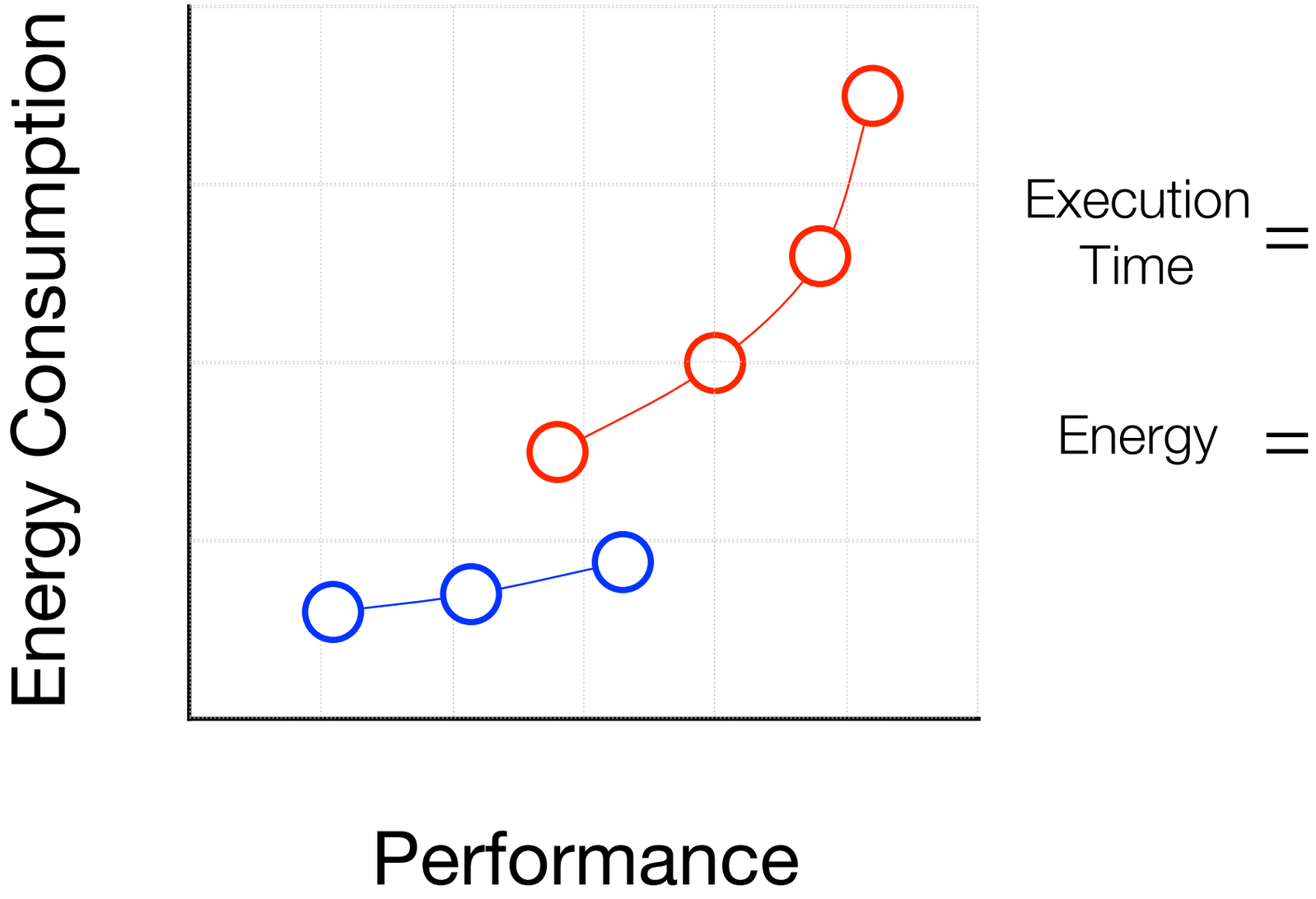
Different Strategies for Different Events

Interactions	WebRT Component
Loading 	Proactive Mechanism
Touching	Adaptive Mechanism
Moving	

Different Strategies for Different Events

Interactions	WebRT Component
Loading	Proactive Mechanism
Touching 	Adaptive Mechanism
Moving 	

ACMP-based **GreenWeb** Runtime



[PLDI 2003] Xie, et al., “Compile-Time Dynamic Voltage Scaling Settings: Opportunities and Limits”

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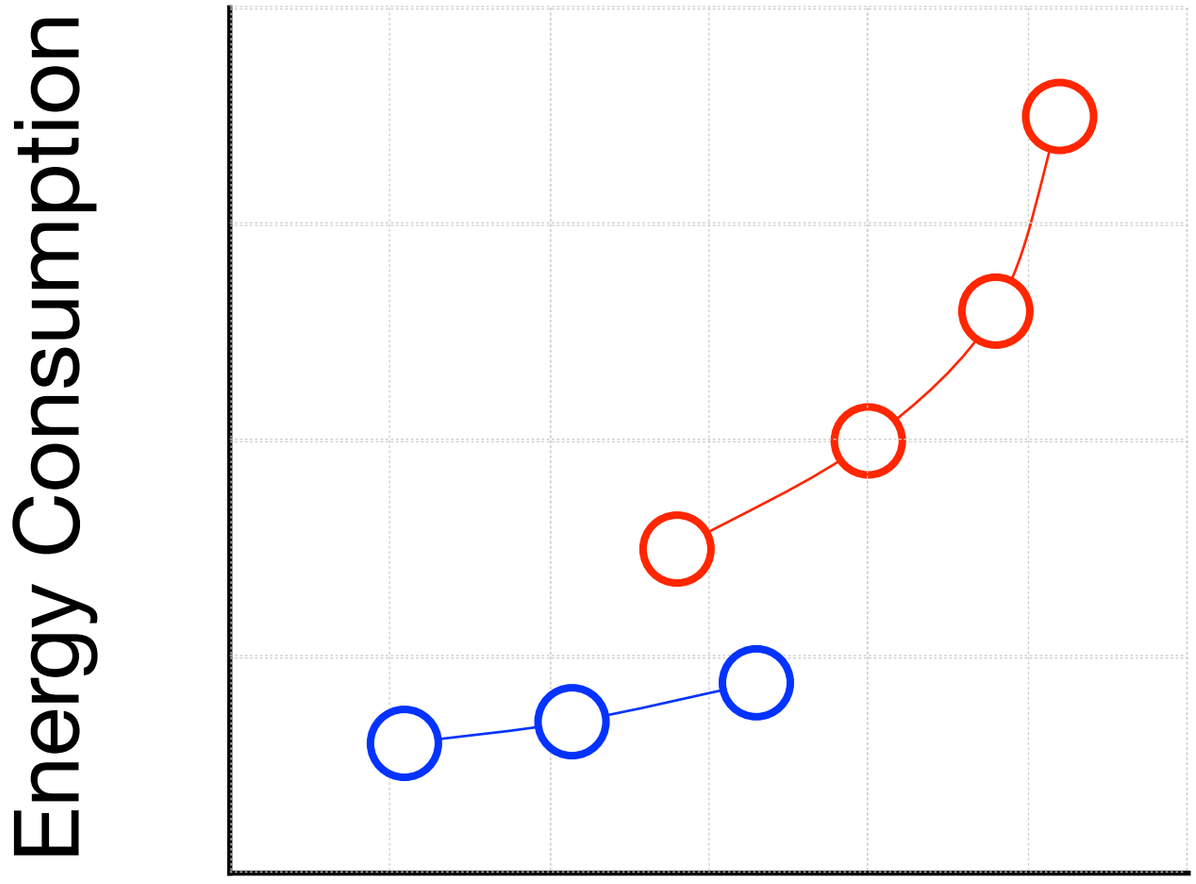
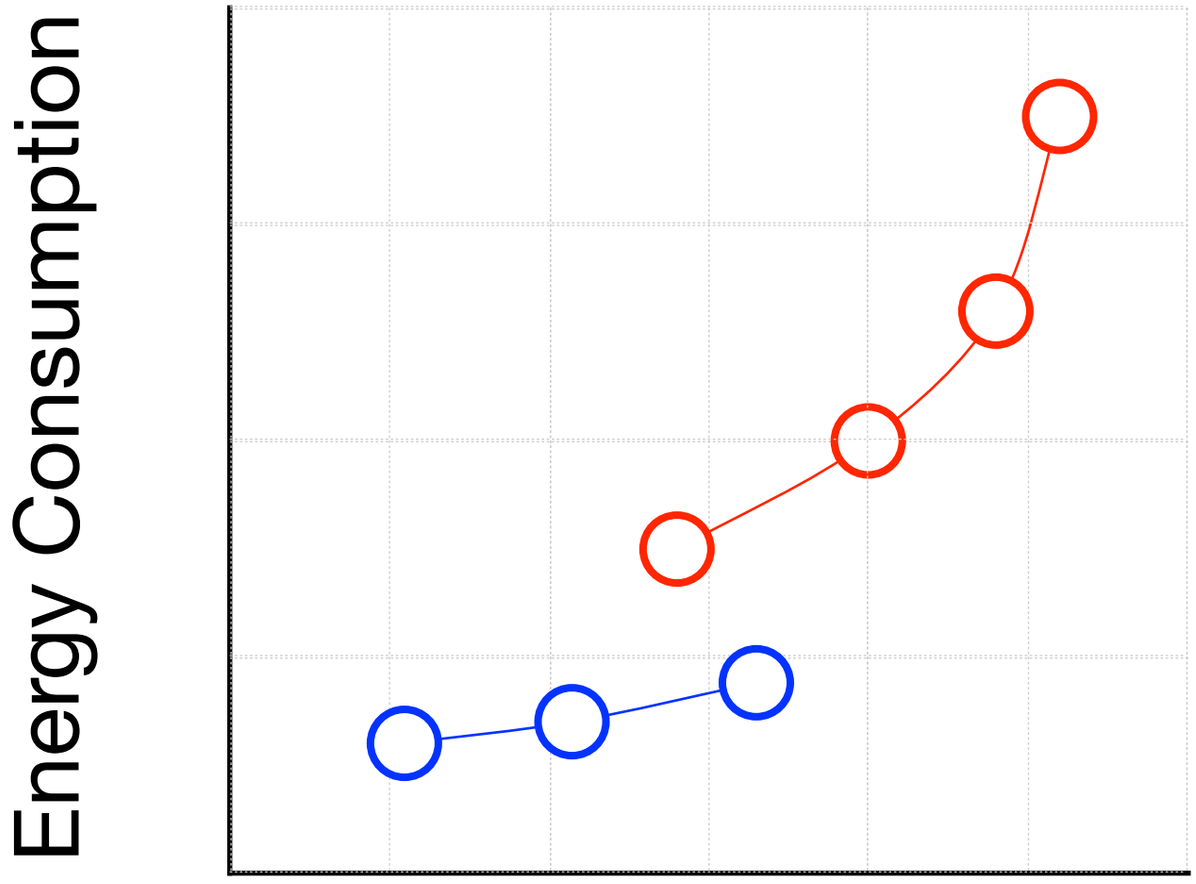


Execution Time = T_{memory} +

Energy =

[PLDI 2003] Xie, et al., “Compile-Time Dynamic Voltage Scaling Settings: Opportunities and Limits”

ACMP-based **GreenWeb** Runtime



$$\text{Execution Time} = T_{memory} + T_{cpu}$$

$$\text{Energy} =$$

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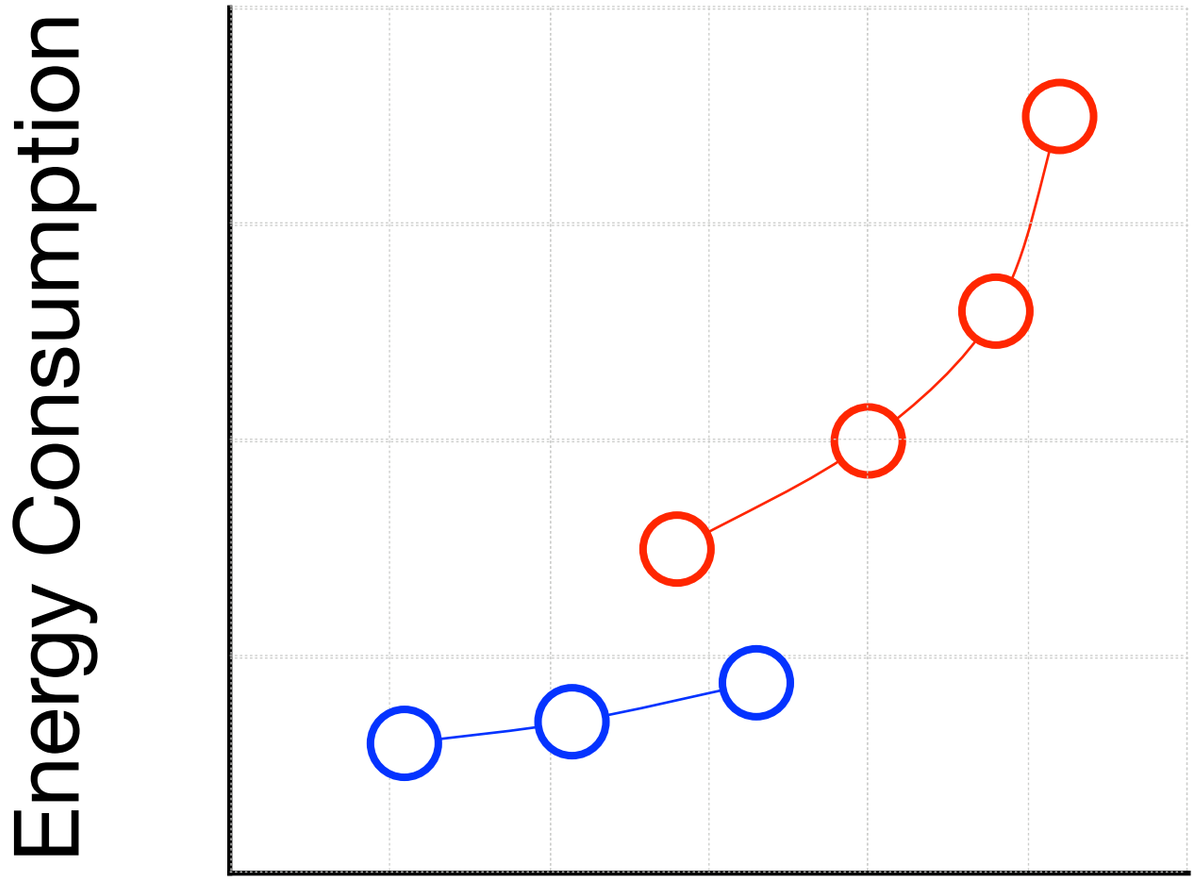
ACMP-based **GreenWeb** Runtime



$$\text{Execution Time} = T_{memory} + N_{cycles} / f$$

$$\text{Energy} =$$

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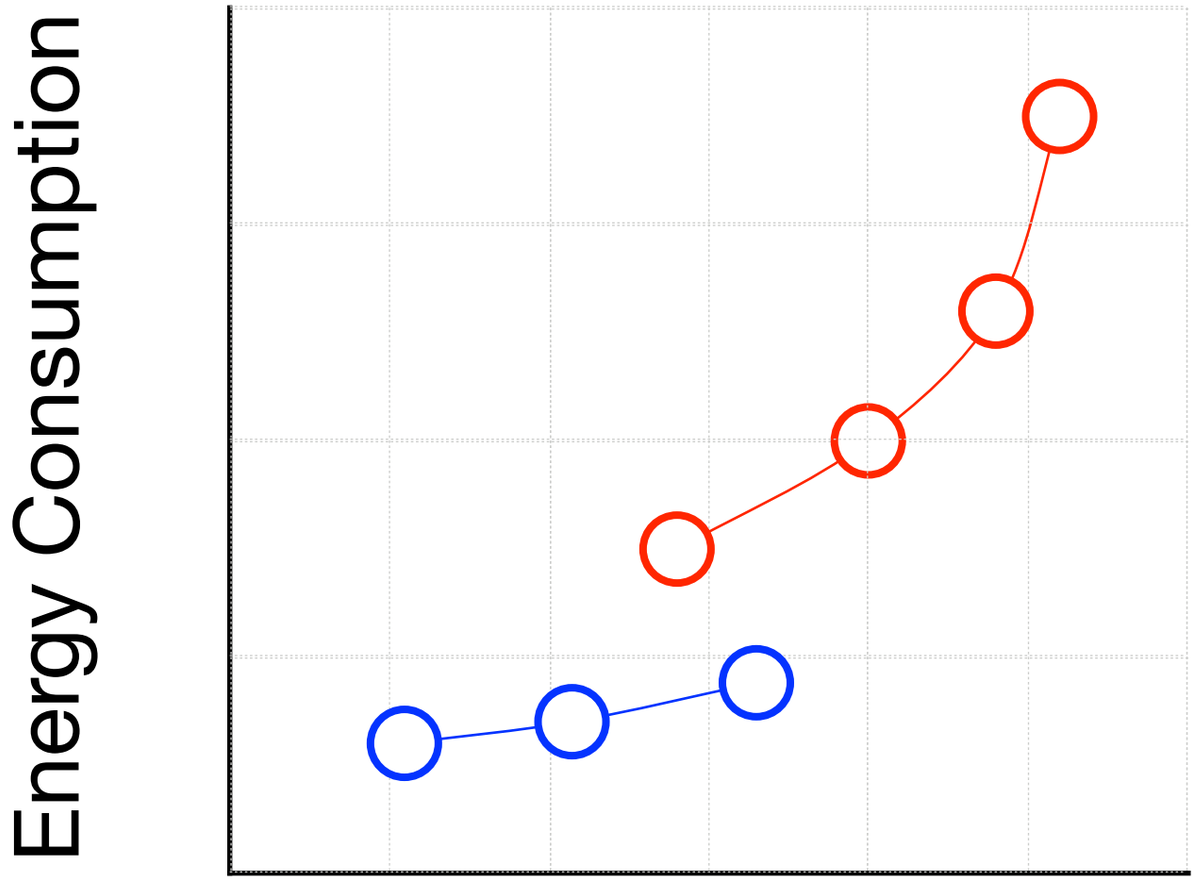
ACMP-based **GreenWeb** Runtime



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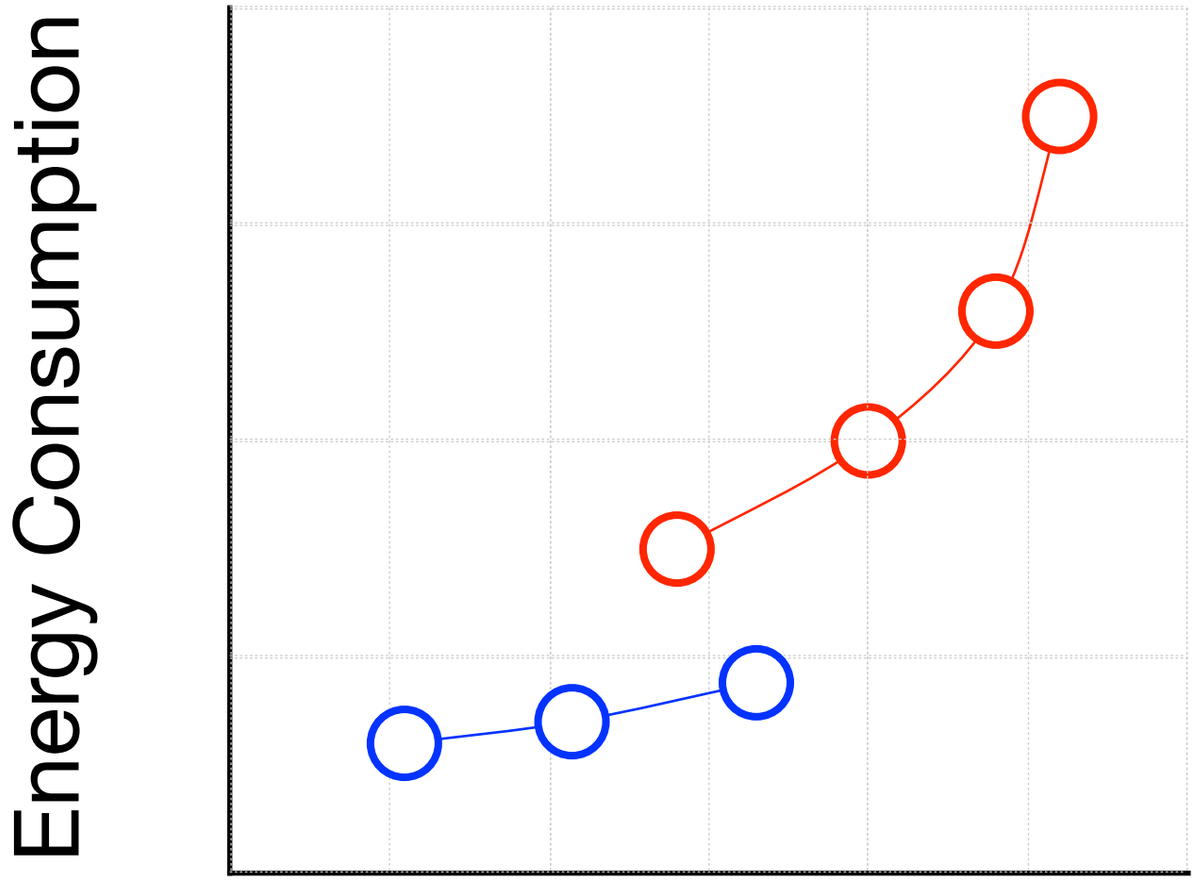

$$\text{Execution Time} = T_{memory} + N_{cycles} / f$$

$$\text{Energy} = \text{Execution Time} \times \text{Power}$$

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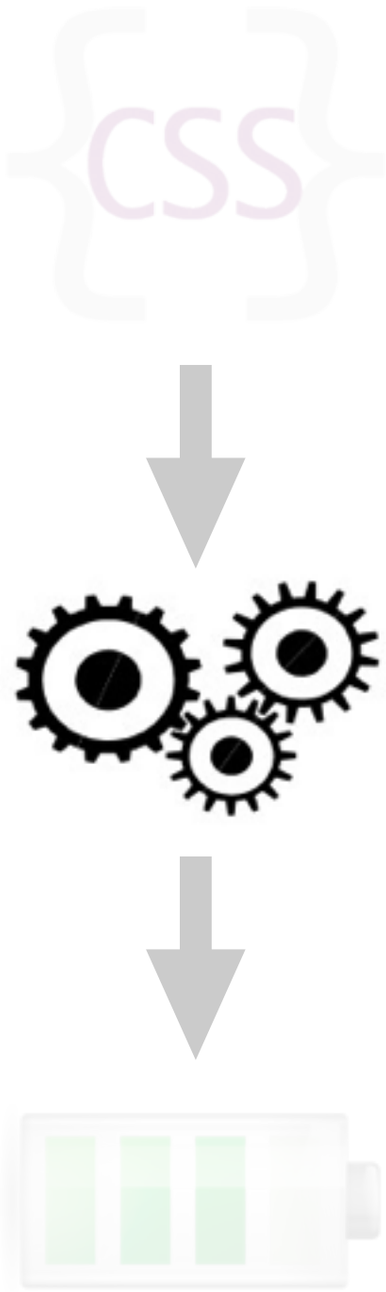
GreenWeb: Language for Energy-Efficiency



- Language abstractions
- **Runtime** that saves energy while meeting the QoS constraints
- Result
  hardware/software implementations

GreenWeb: Language for Energy-Efficiency

- Language abstractions

- Runtime
  the QoS constraints

- **Result** in 60% energy savings on real hardware/software implementations

Real Hardware/Software Setup

ODroid XU+E development board, which contains an Exynos 5410 SoC used in Samsung Galaxy S4.

Real Hardware/Software Setup

ODroid XU+E development board, which contains an Exynos 5410 SoC used in Samsung Galaxy S4.

Big core cluster: ARM Cortex A15, OoO with 3 issue

Little core cluster: ARM Cortex A7, In-order with 2 issue

Overhead:

- Frequency switch: 100 us
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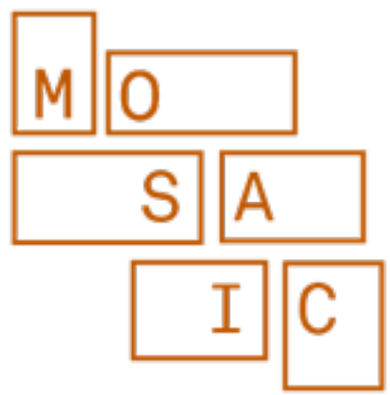
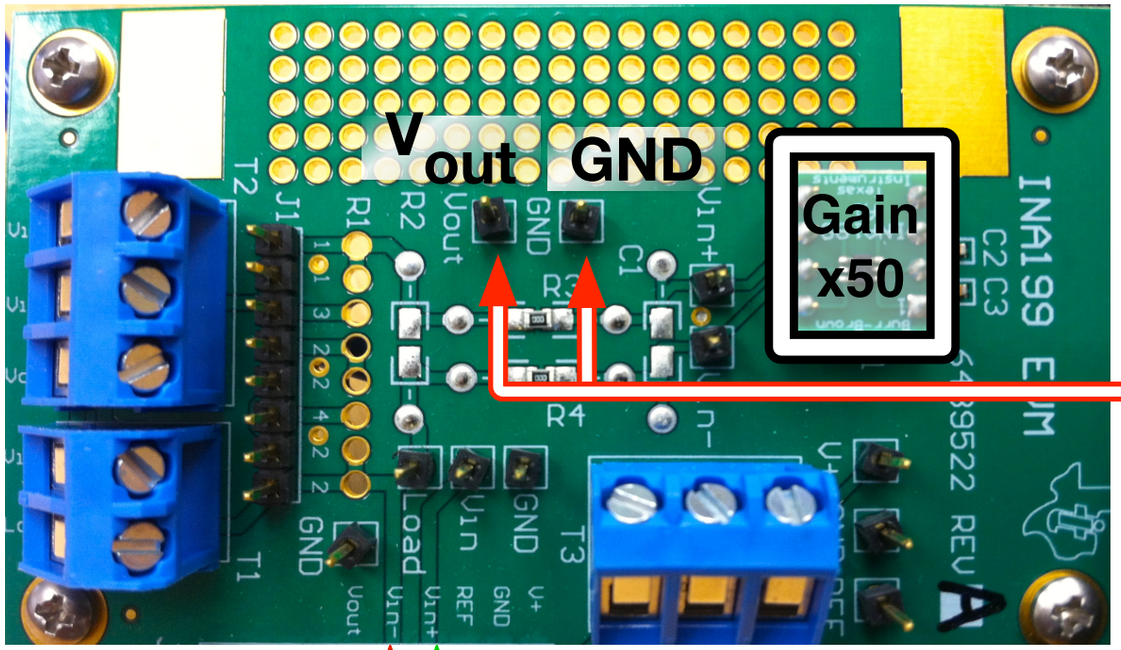


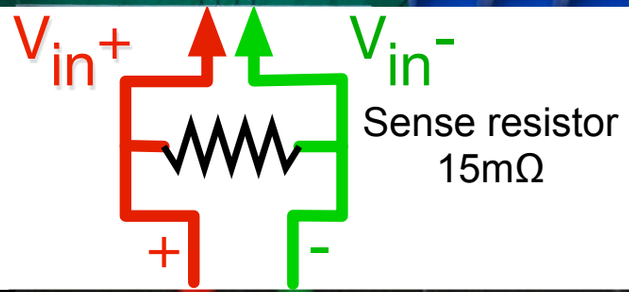
UI-level record and replay for reproducibility. [ISPASS'15]

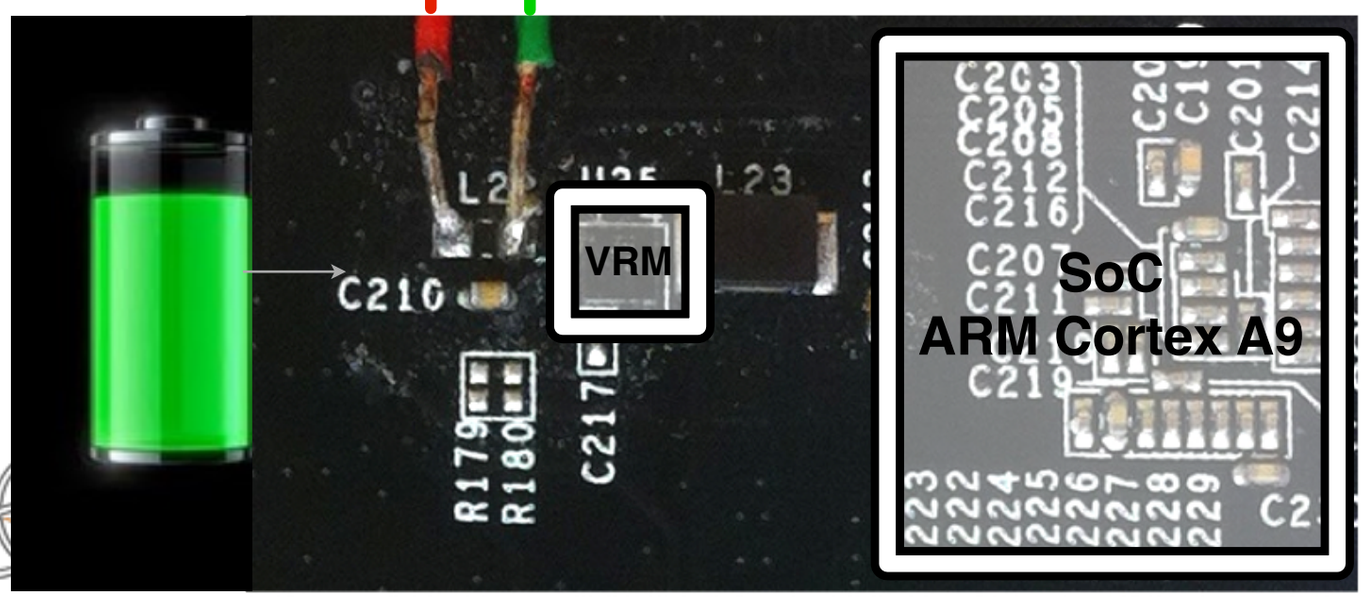
Power and Energy Measurements



Probe

Data Acquisition
(DAQ)





$$\text{Power} = (V_{in}^{+} - V_{in}^{-}) / R_{sense} * V_{in}^{-}$$

Evaluation

- Baseline Mechanisms
  - Highest performance (**Perf**) — Standard to guarantee responsiveness
  - Interactive governor (**Interactive**) — Android default

Evaluation

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  - Energy Saving
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Evaluation

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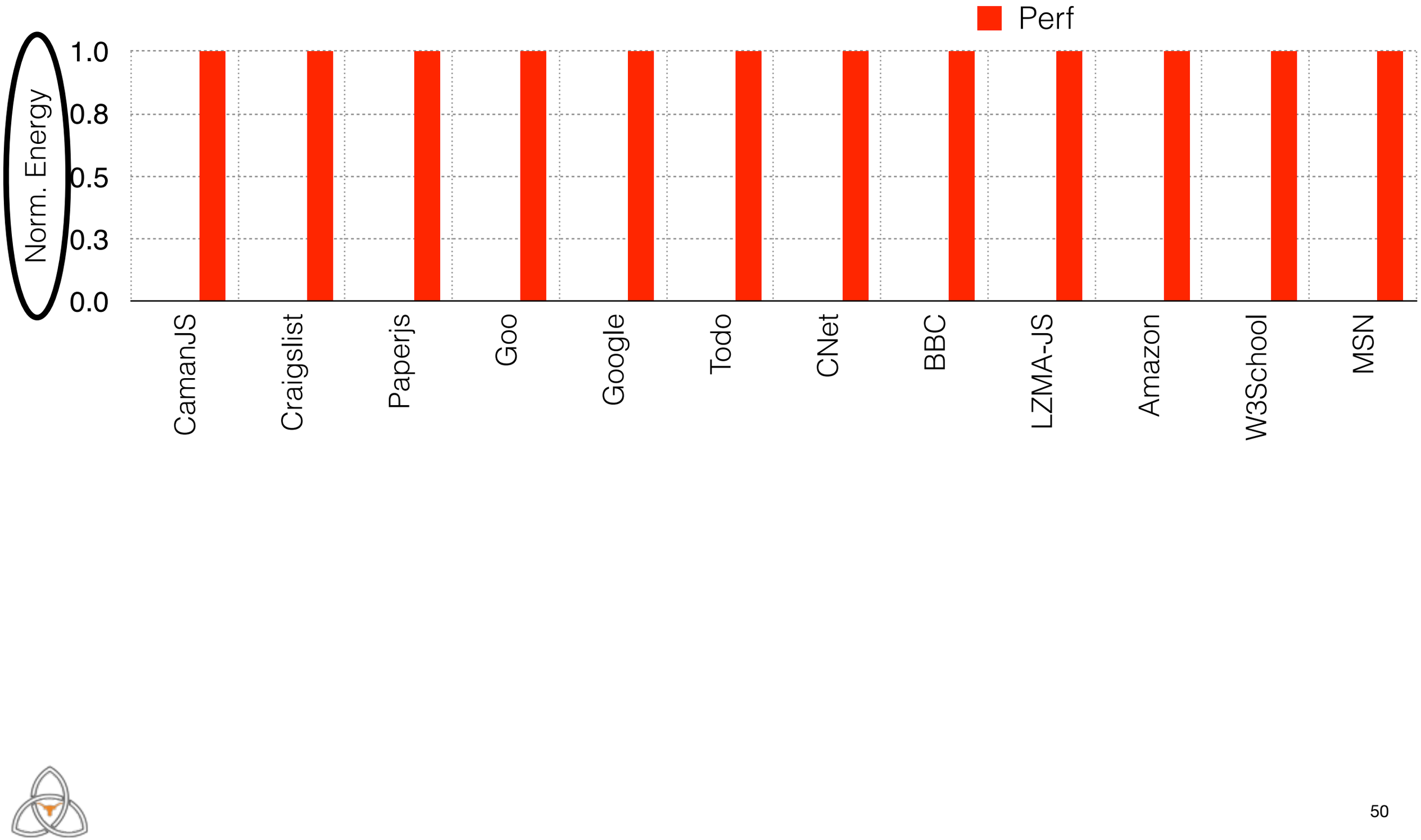
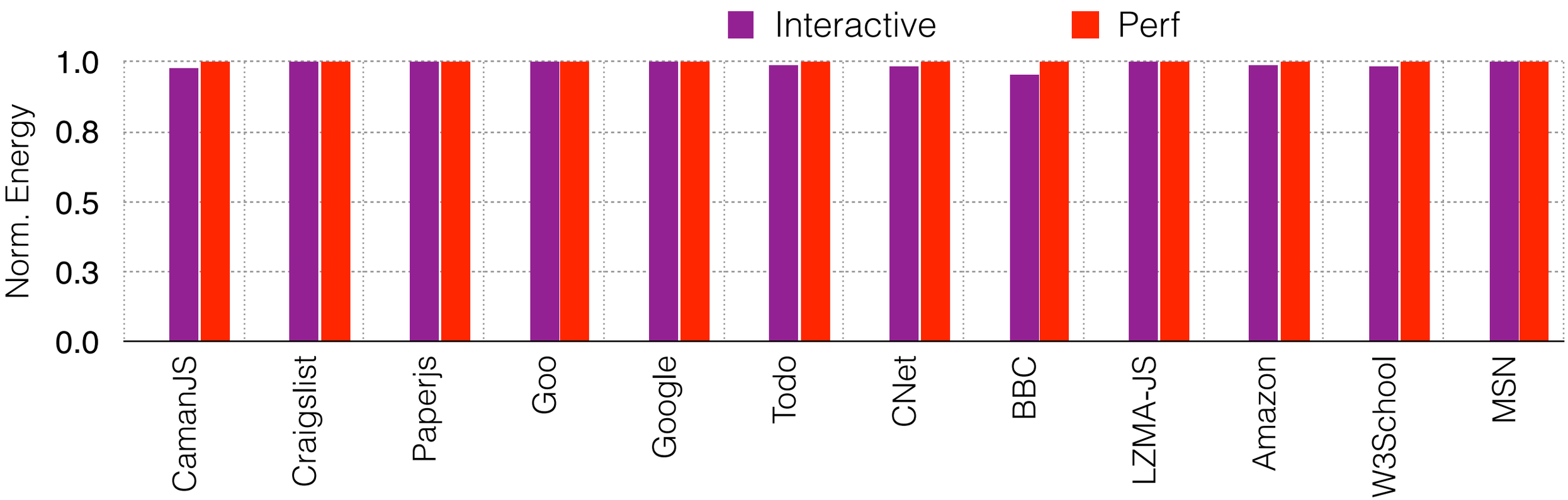
  - Highest performance (**Perf**) — Standard to guarantee responsiveness
  - Interactive governor (**Interactive**) — Android default
- Metrics
  - Energy Saving
  - QoS Violation
- Applications
  - Top webpages (e.g., www.amazon.com)
  - Web Apps based on popular frameworks (e.g., Todo List)

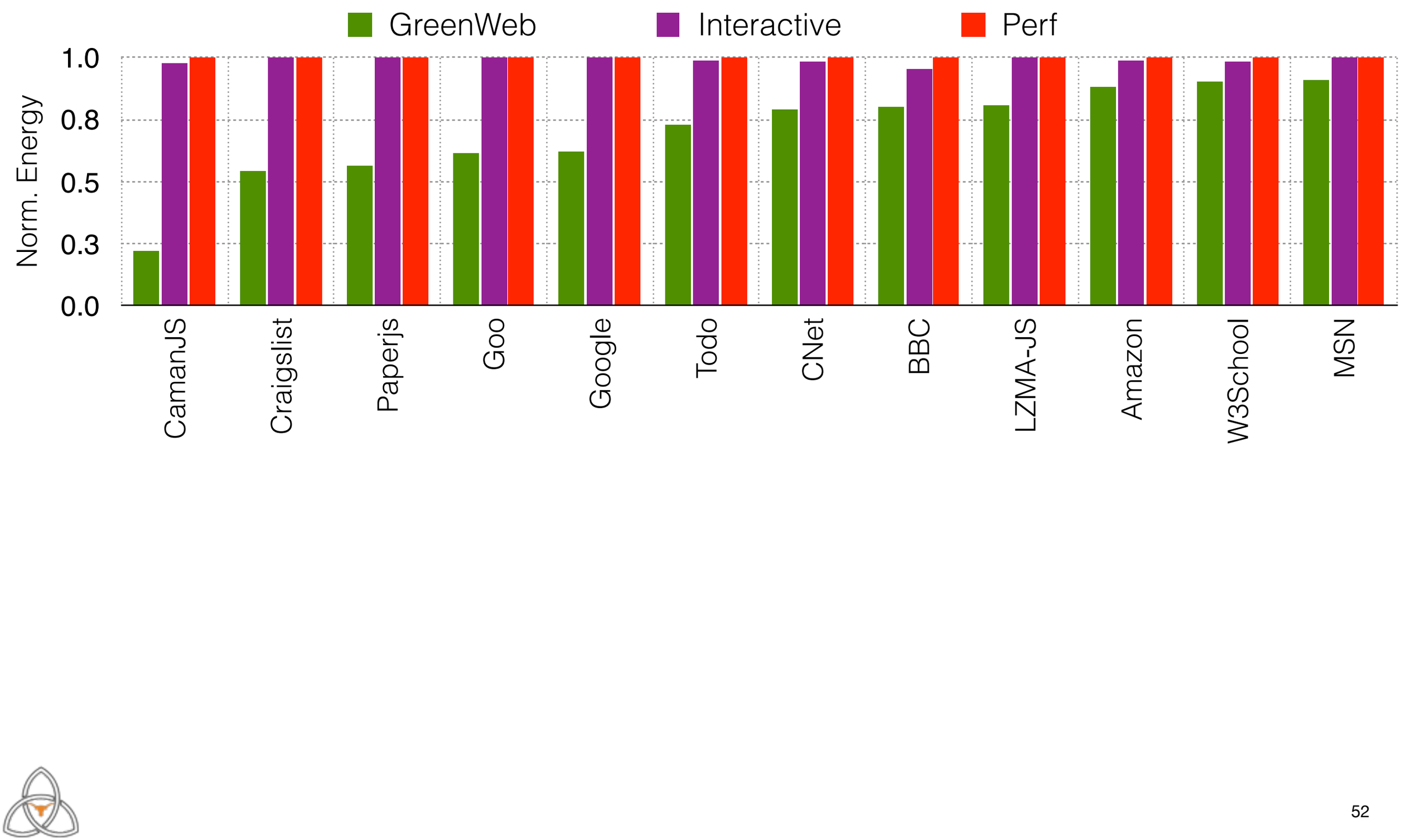
Evaluation Results



Evaluation Results



Evaluation Results



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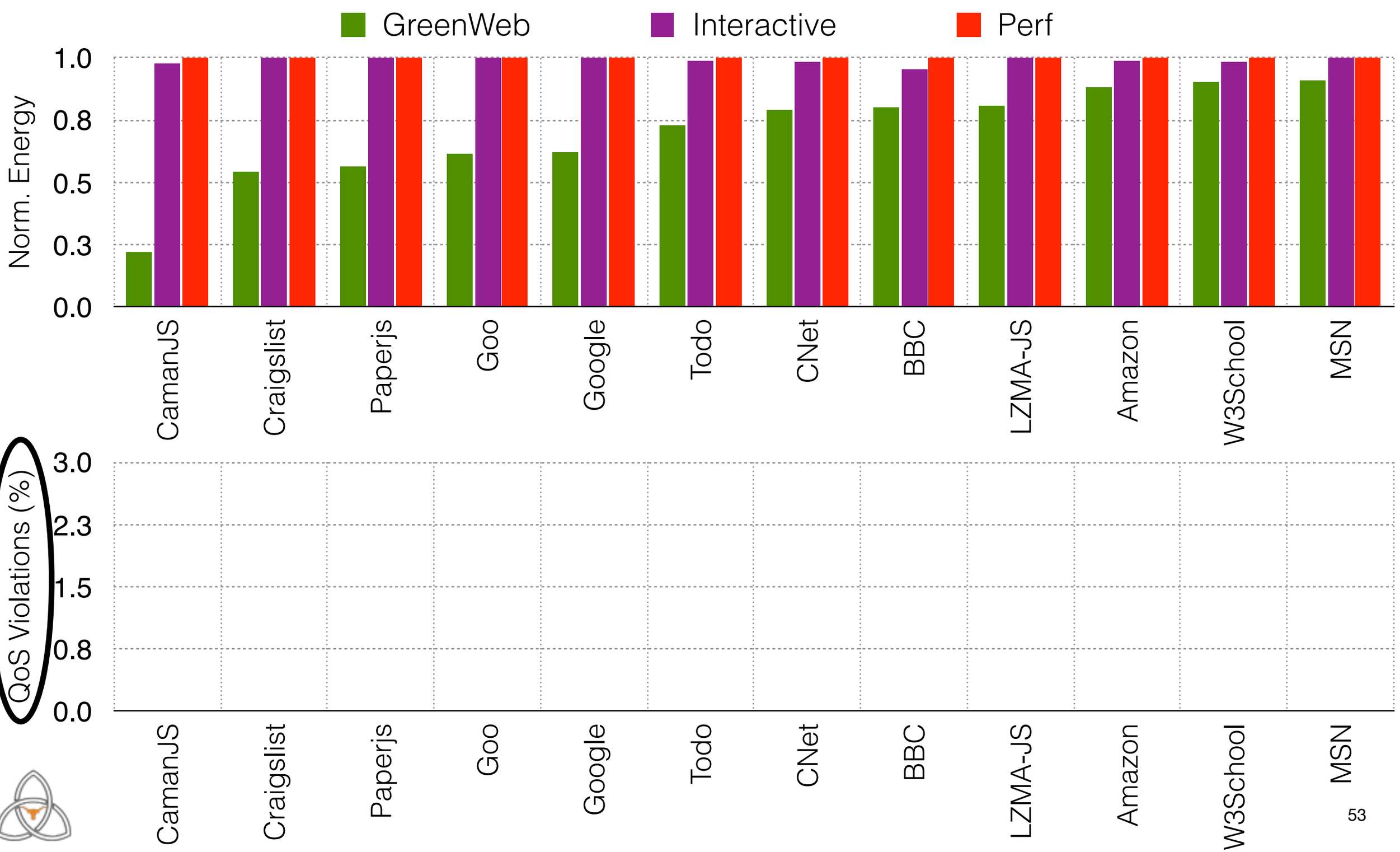

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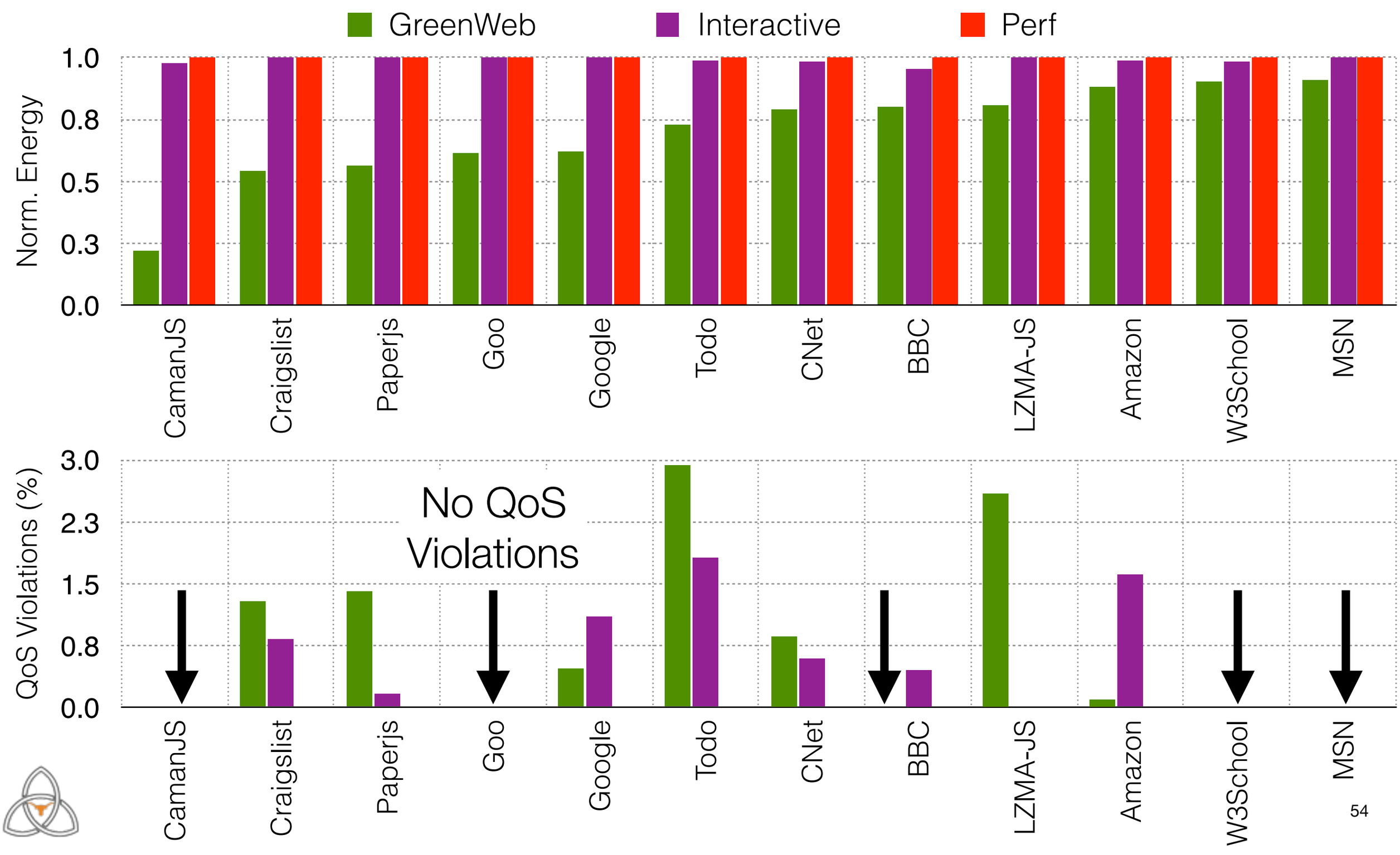
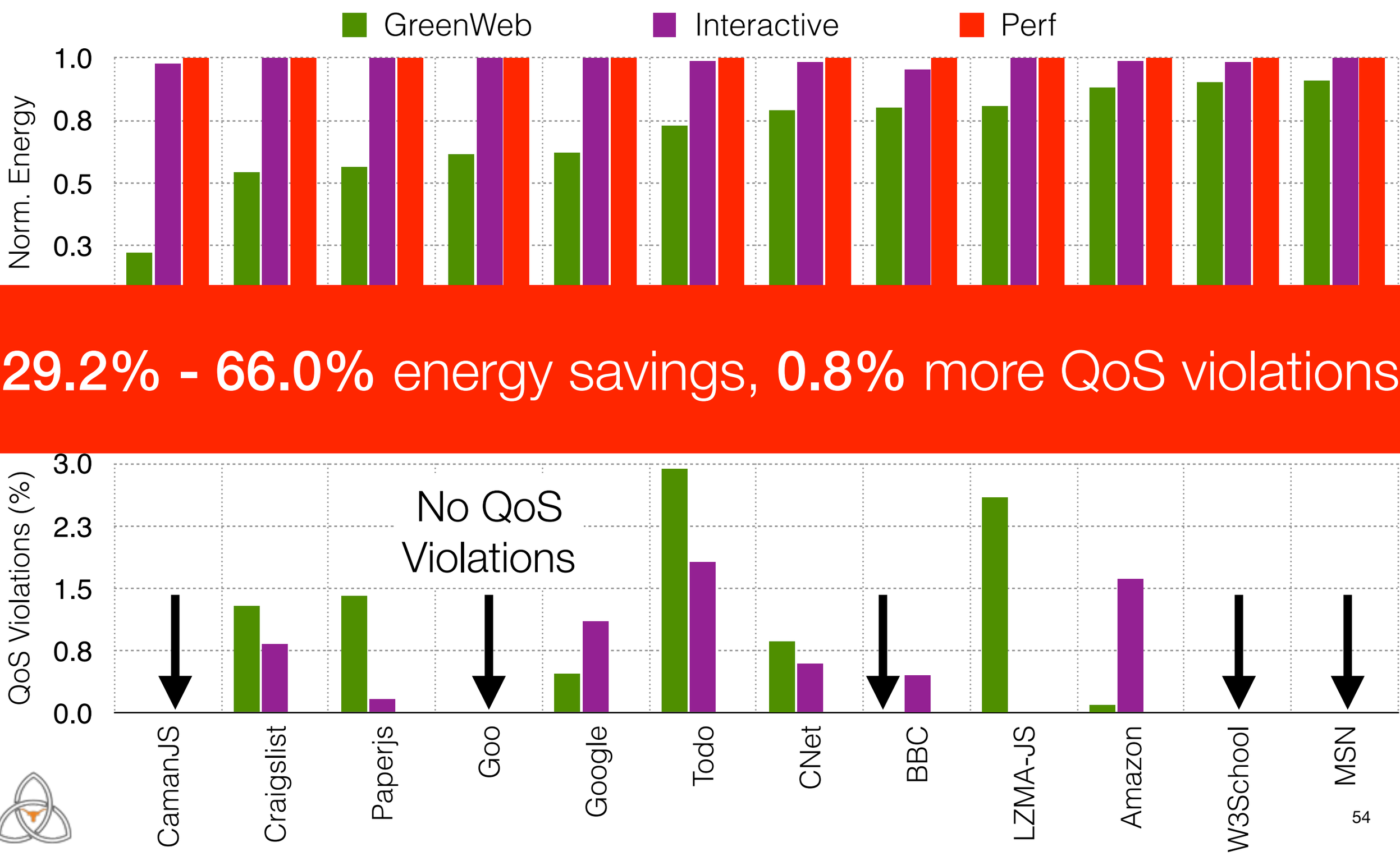
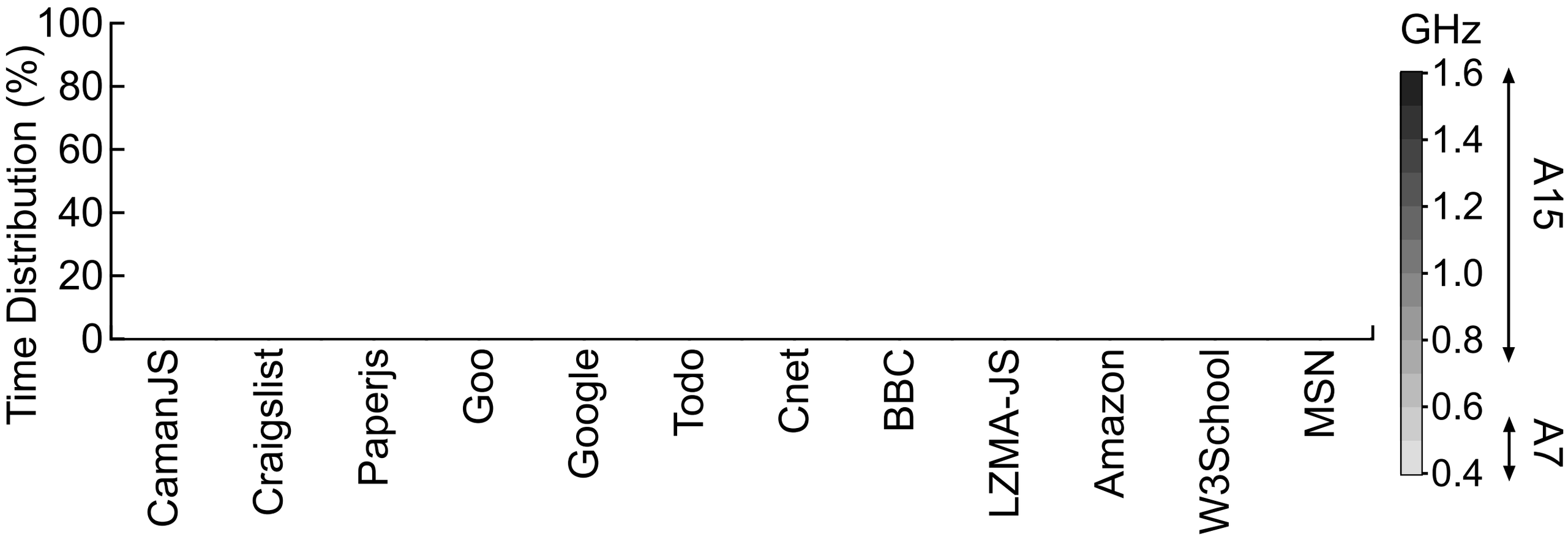


Evaluation Results



29.2% - 66.0% energy savings, **0.8%** more QoS violations

Architecture Configuration Distribution



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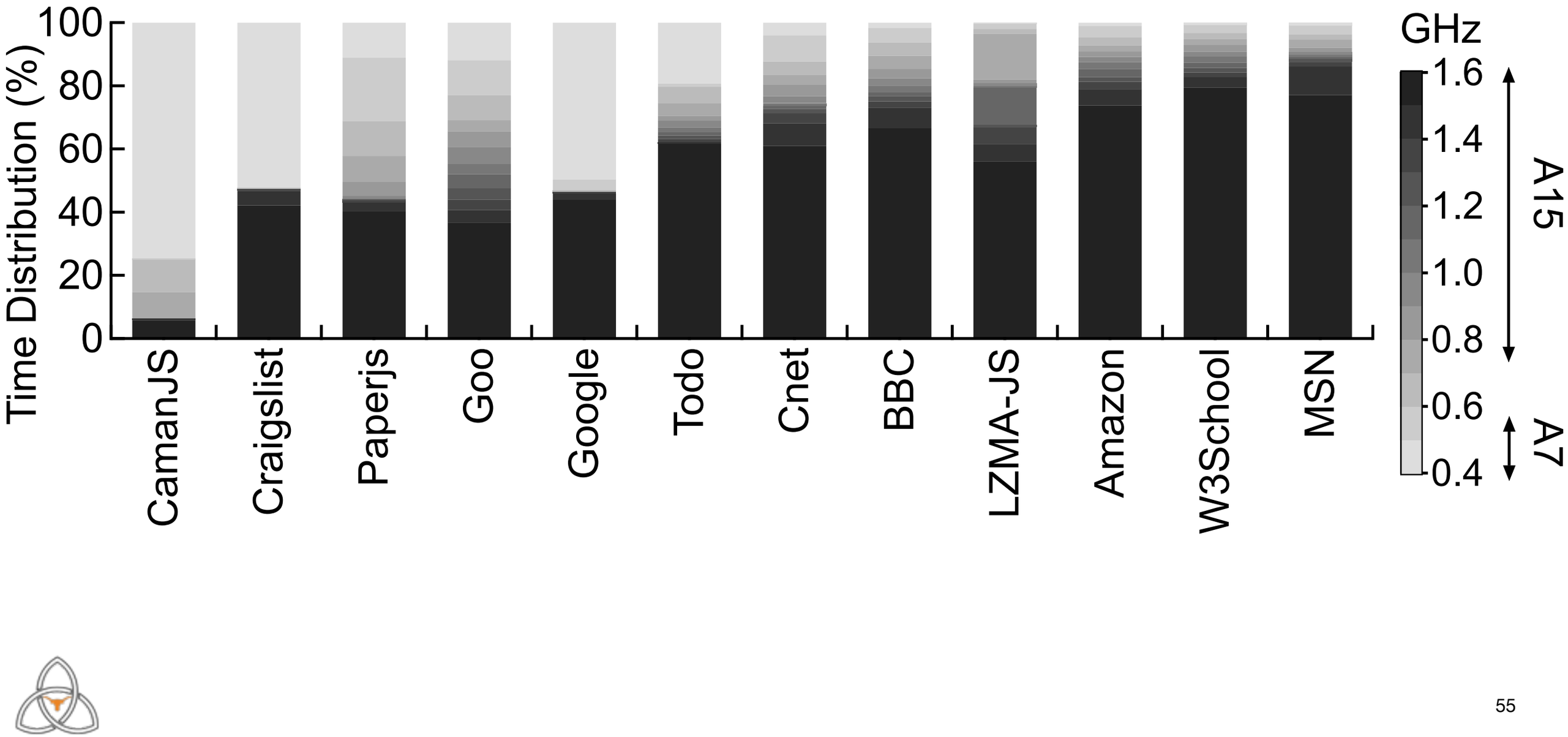

GreenWeb

Programming language support for balancing energy-efficiency and QoS in mobile Web computing

GreenWeb

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Abstraction

Express QoS constraints

GreenWeb

Programming language support for balancing energy-efficiency and QoS in mobile Web computing

Abstraction

Express QoS constraints

Runtime

Satisfy QoS specifications using energy saving techniques

GreenWeb

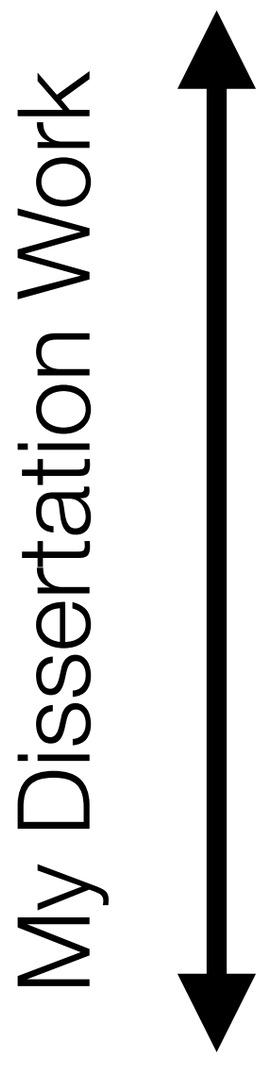
Programming language support for balancing energy-efficiency and QoS in mobile Web computing

Abstraction — Express QoS constraints

Runtime — Satisfy QoS specifications using energy saving techniques

Effect — Significant energy savings

My Approach



Application

GreenWeb

Language Extensions

Runtime

WebRT

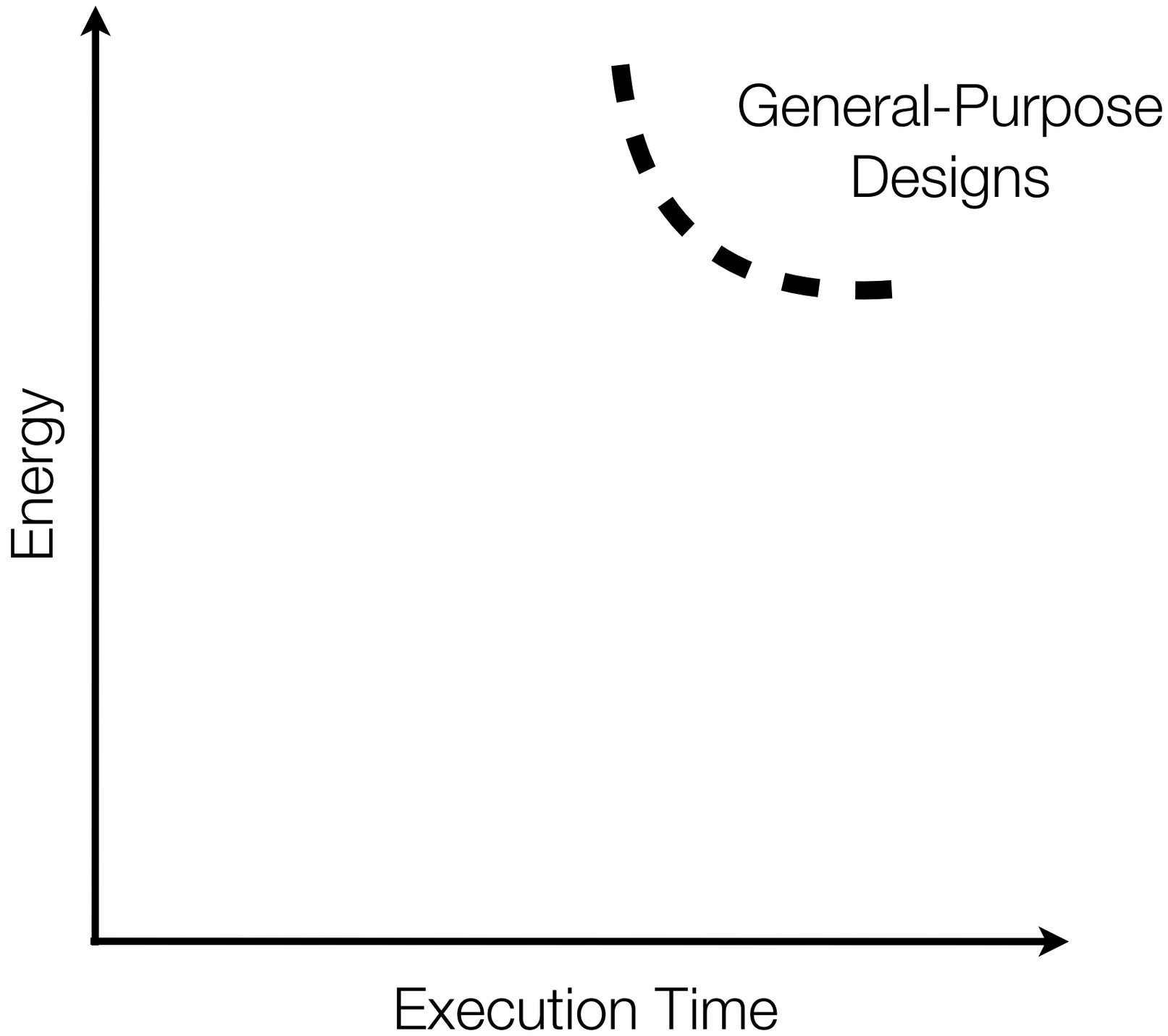
Energy-aware Web Runtime

Architecture

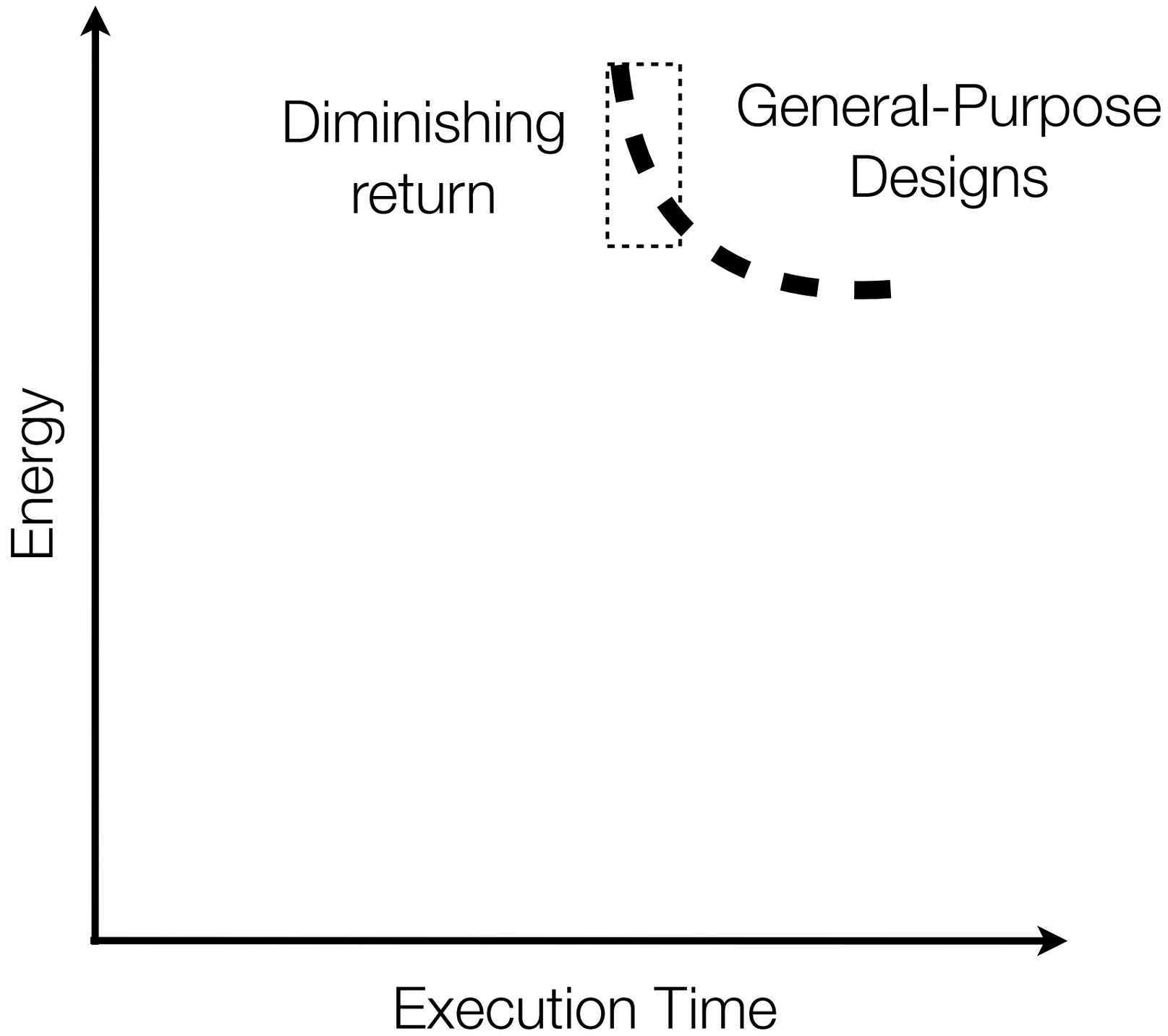
WebCore

Web-specific Architecture

WebCore: a Web-Specific Mobile Architecture



WebCore: a Web-Specific Mobile Architecture



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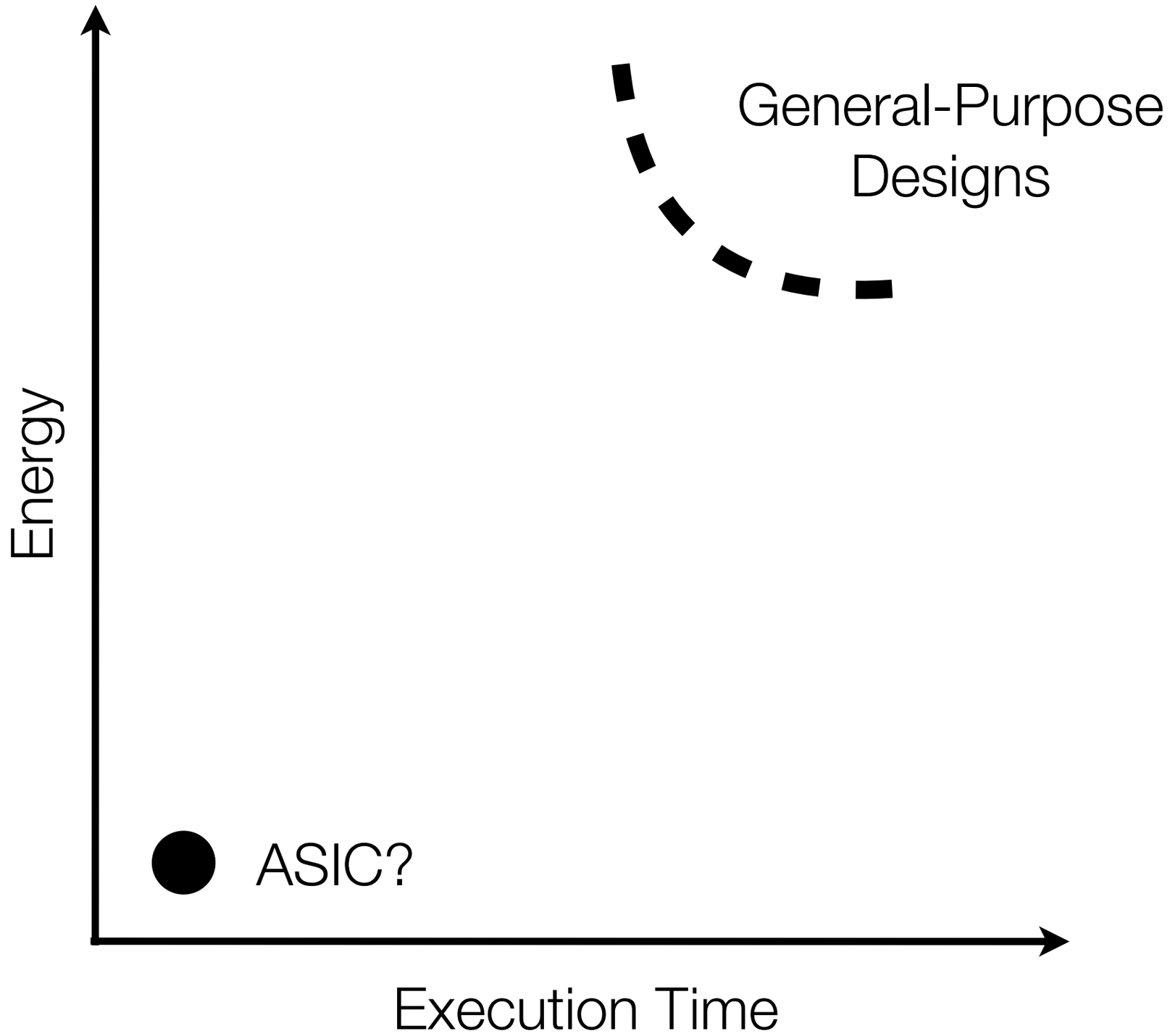

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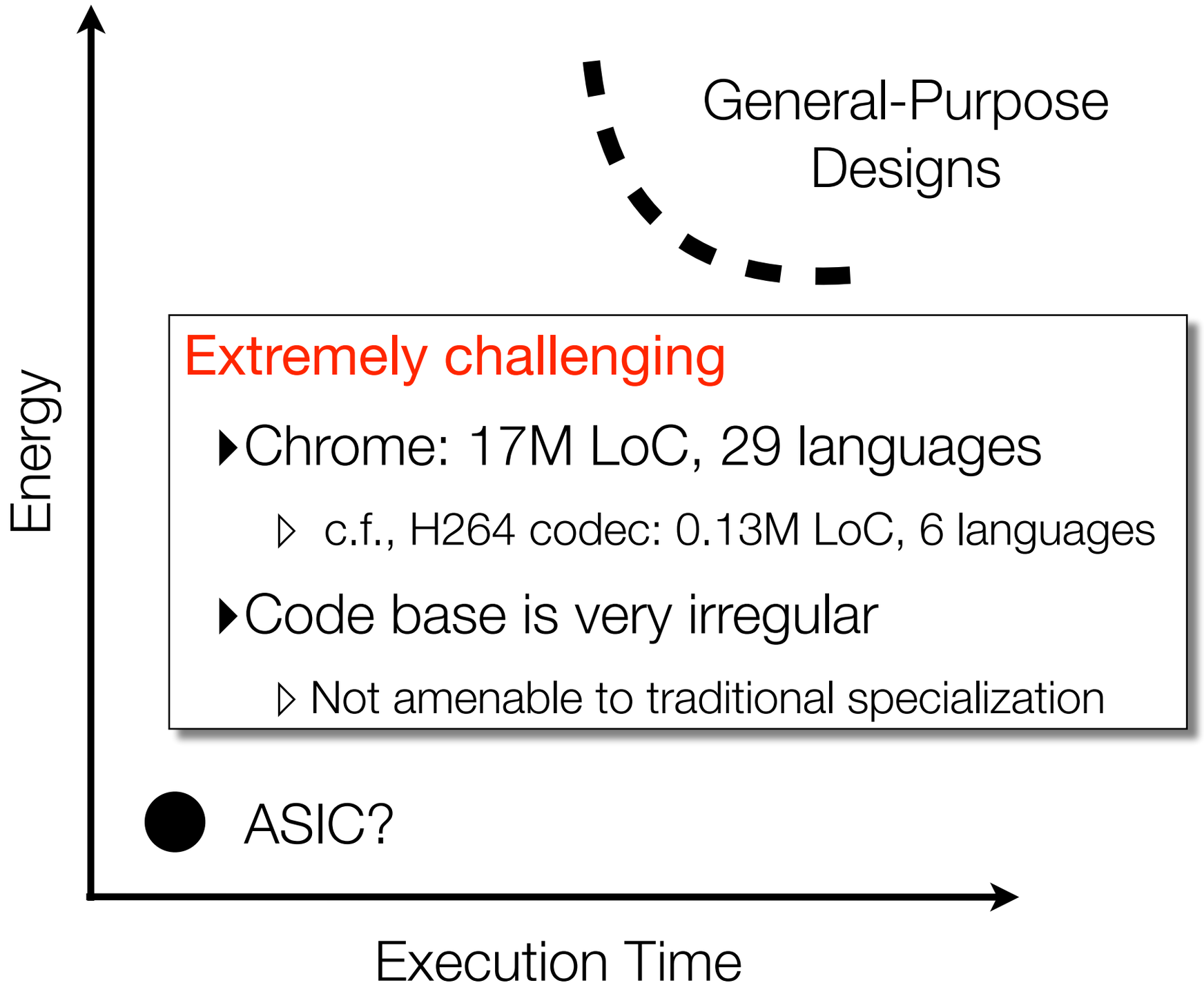

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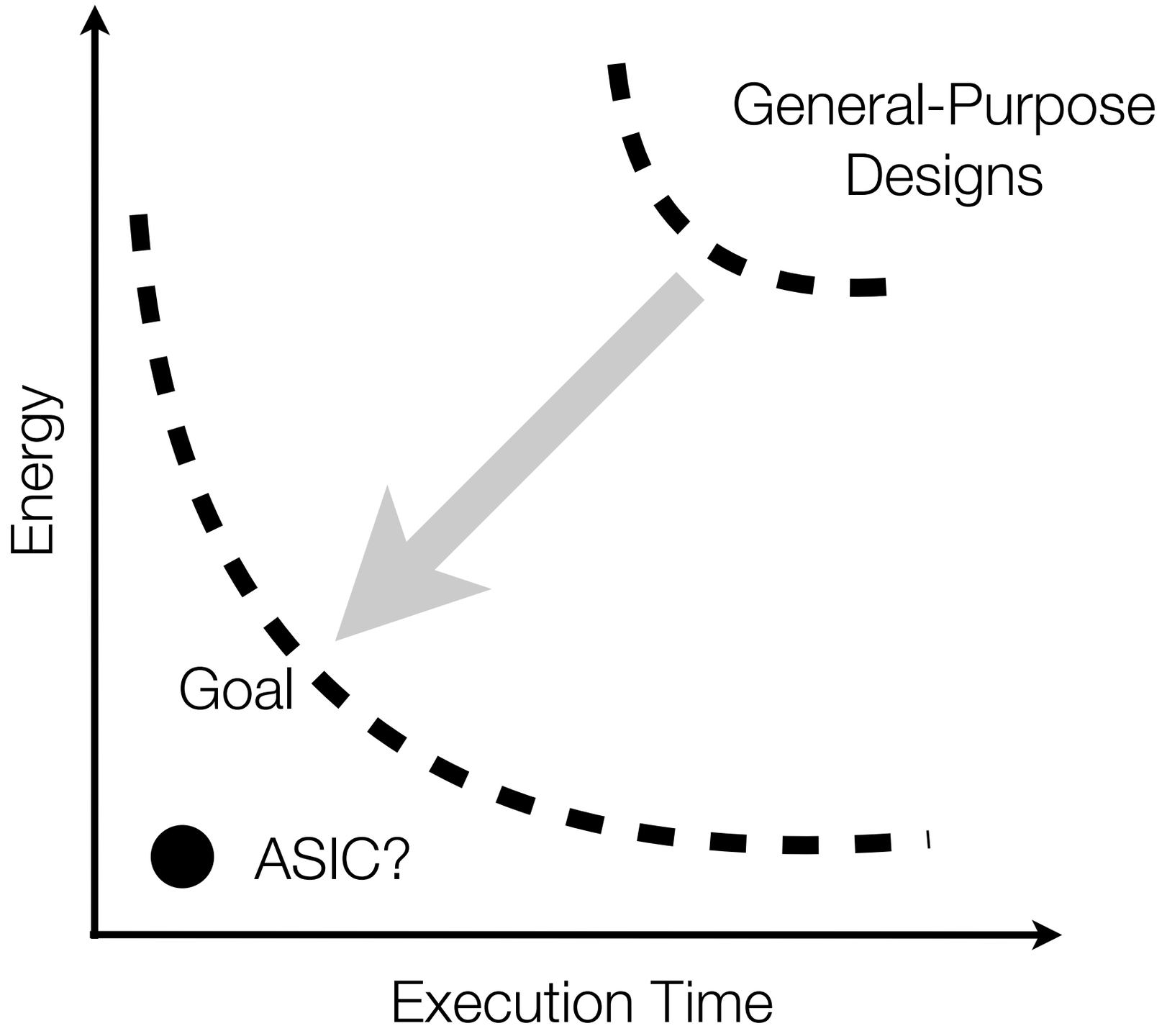

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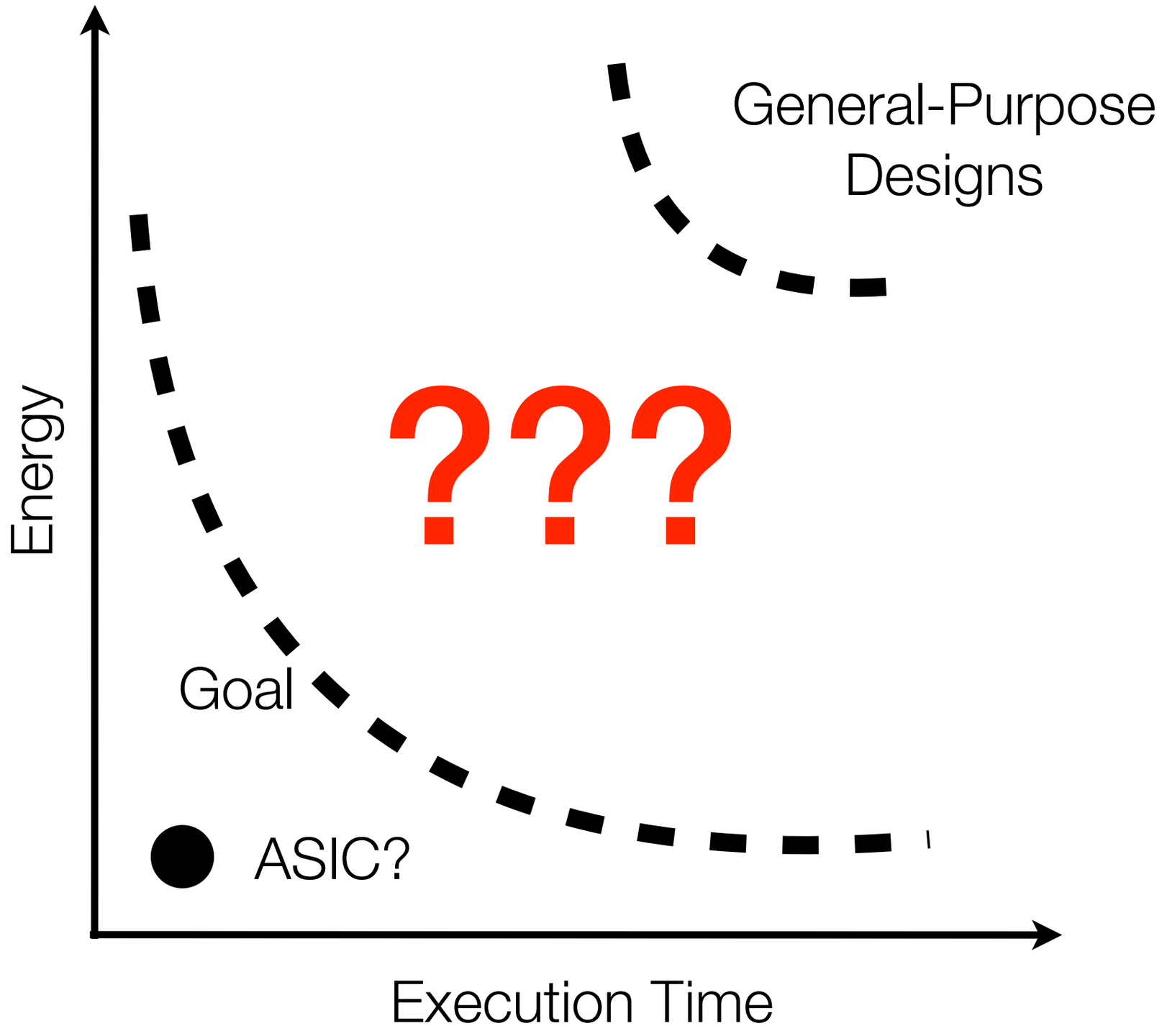

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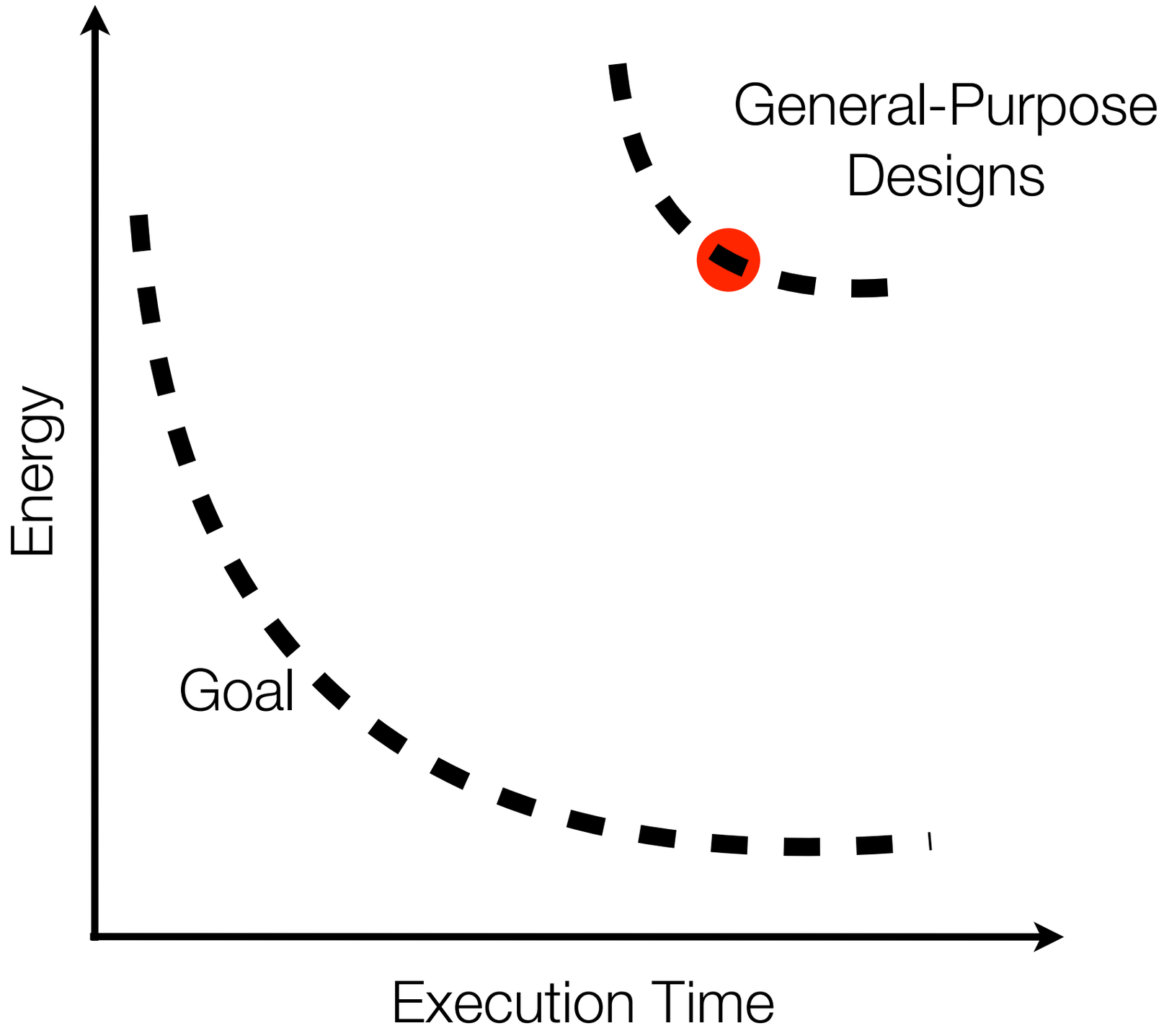

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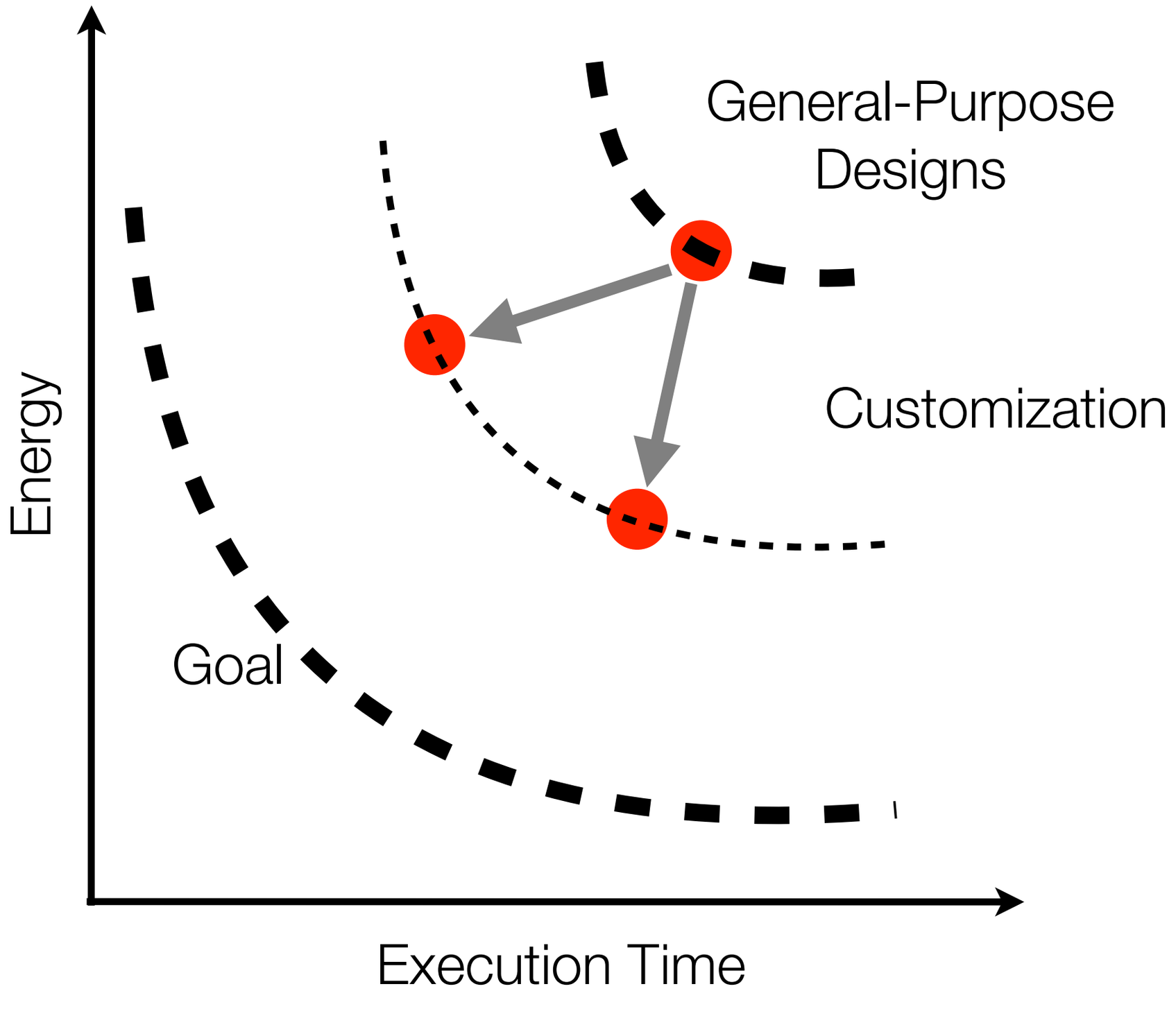

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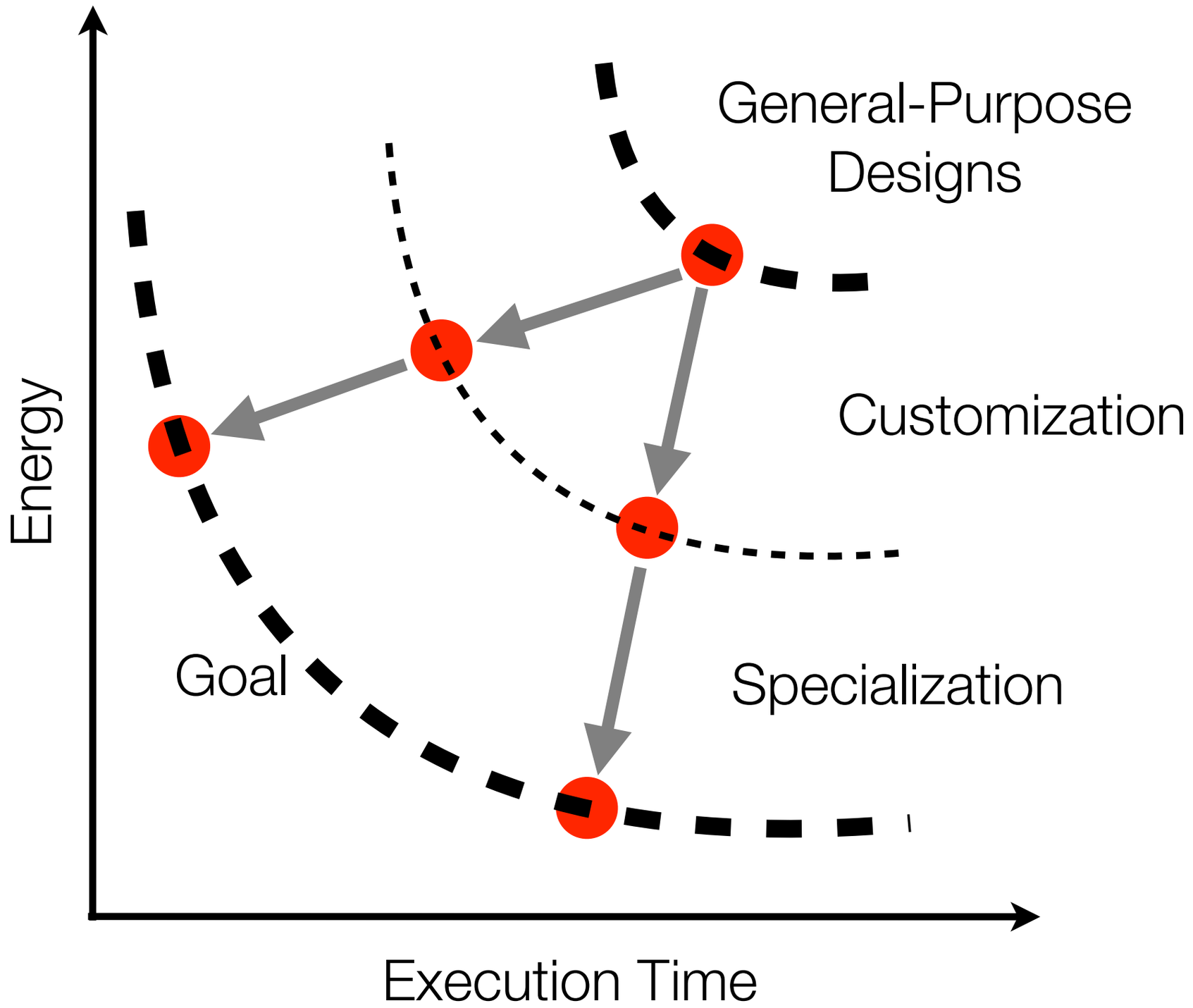

Specialization Target: Style Resolution Kernel

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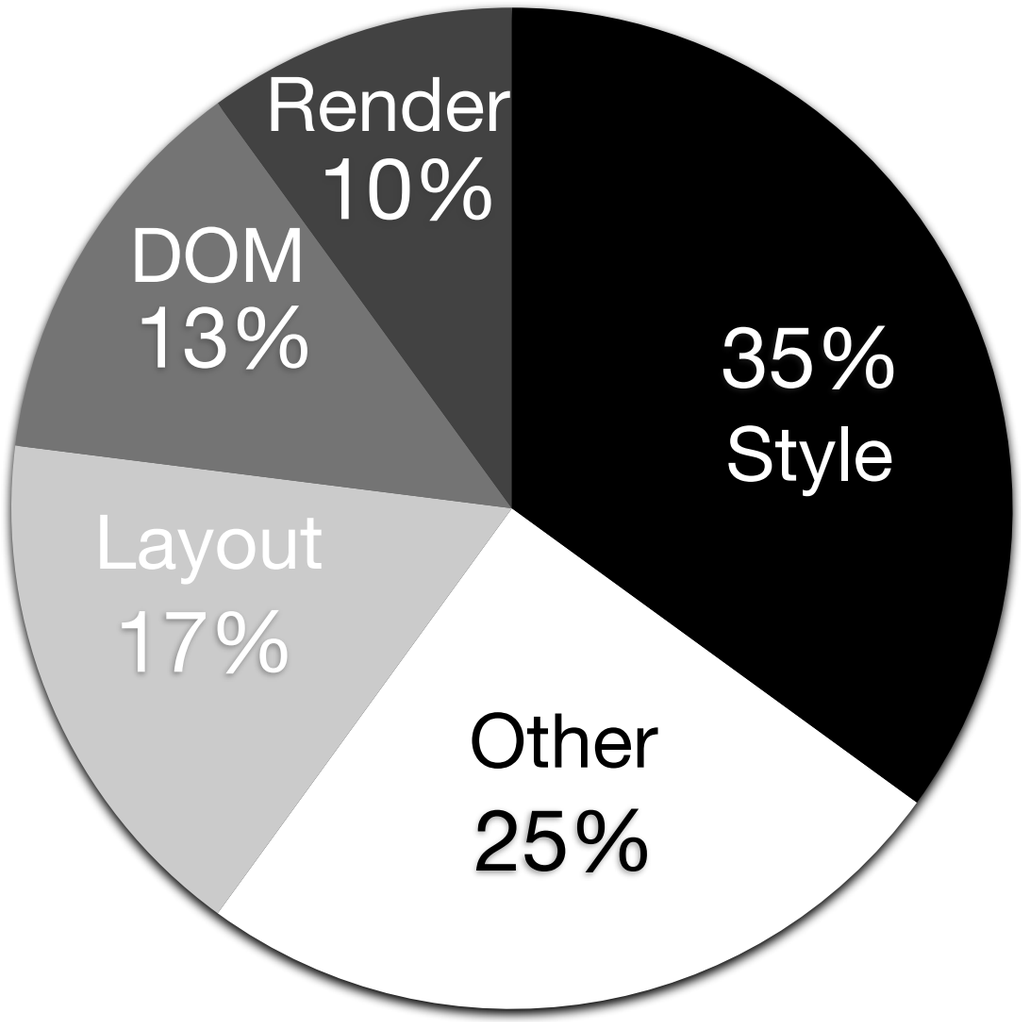
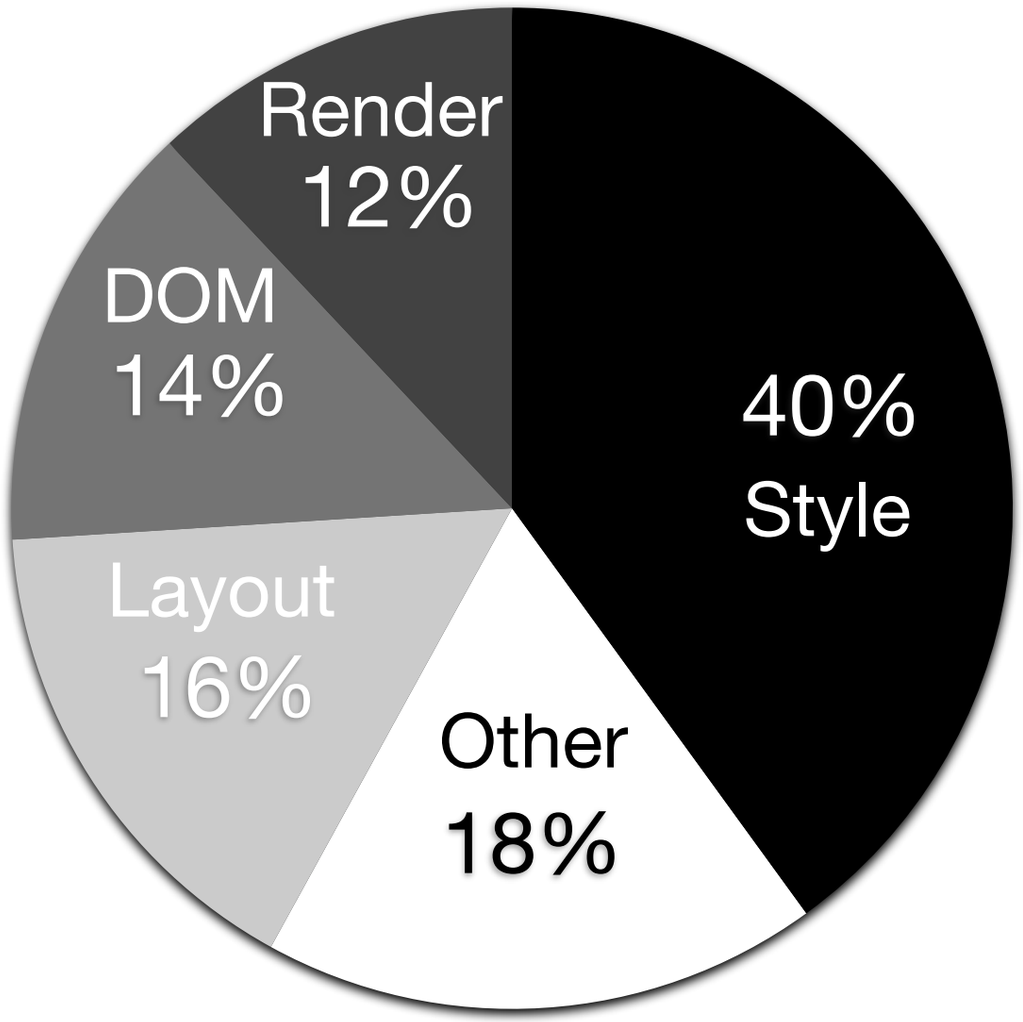


Execution time breakdown



Energy breakdown

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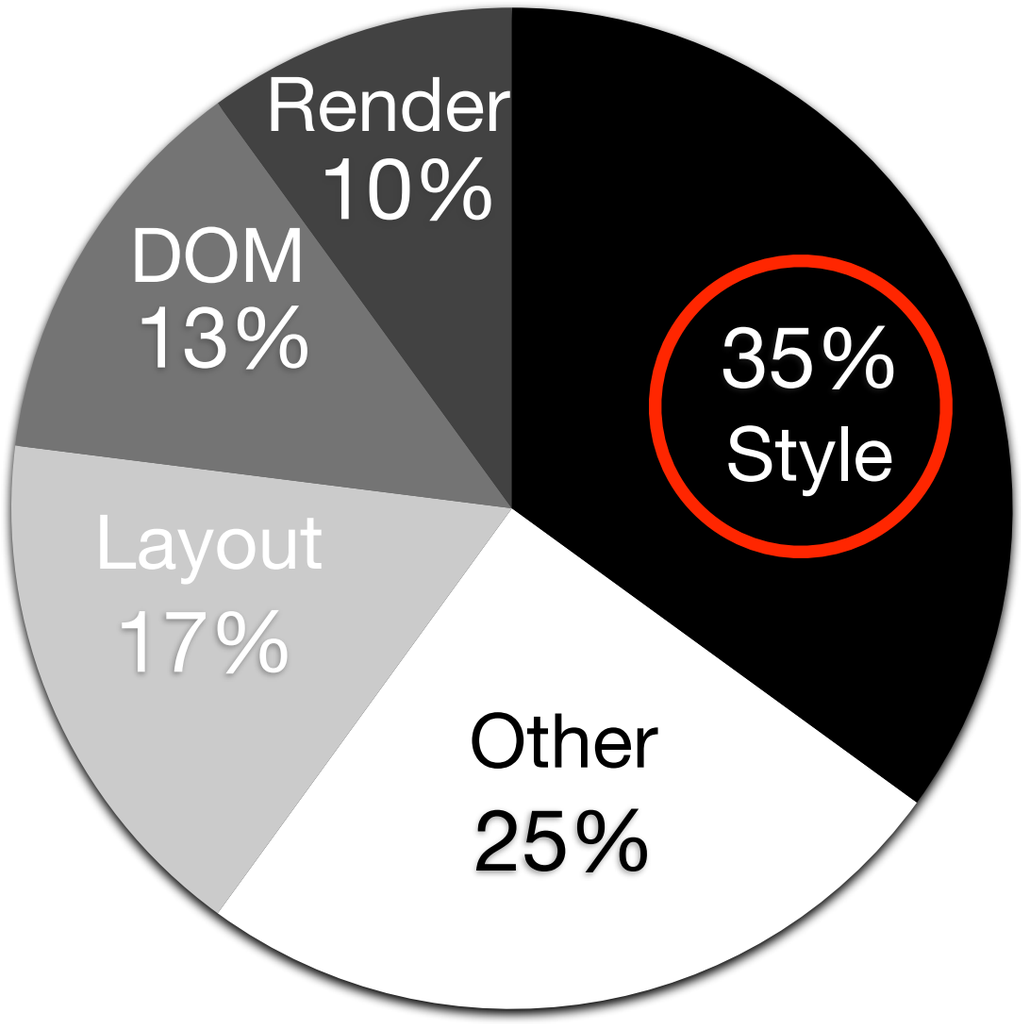

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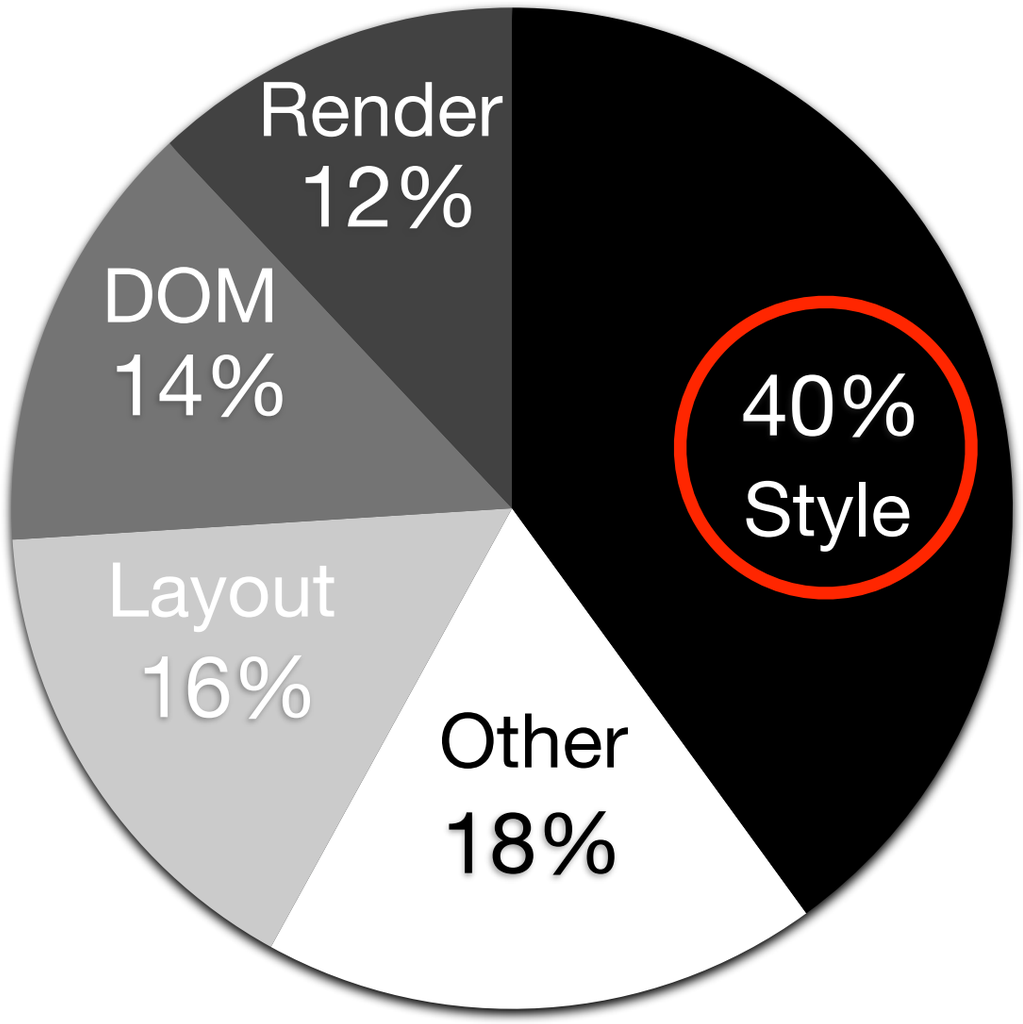

Energy breakdown

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  for (each property in rule) {
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Rule-level Parallelism (RLP)

Specialization Target: Style Resolution Kernel

```
for (each rule in matchedRules) {
  for (each property in rule) {
    switch (property.id) {
      case Font:
        Style[Font] = Handler(property.value, DOMNode);
        break;
      case N: ...}}}
```

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Rule-level Parallelism (RLP)

Property-level Parallelism (PLP)

Specialization Target: Style Resolution Kernel

```
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```

Rule-level Parallelism (RLP)

Property-level Parallelism (PLP)

- Exploiting the parallelism to increase the arithmetic intensity
- Move operands closer to operations to sustain the computations

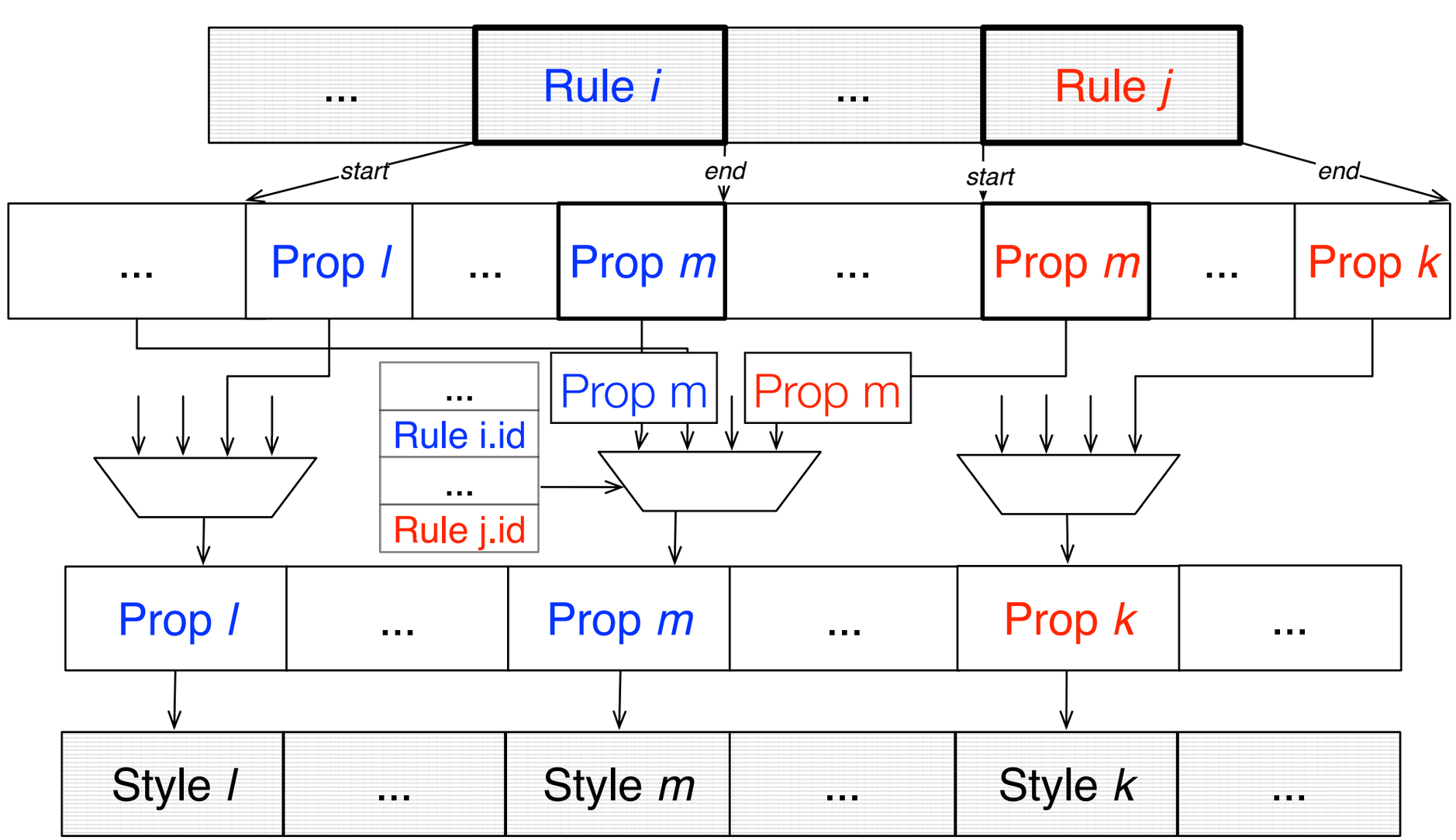
Style Resolution Unit

Input Scratchpad

Conflict Resolution

Compute Lanes

Output Scratchpad



Evaluation Results

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- Fully synthesized using Synopsys 28 nm toolchain

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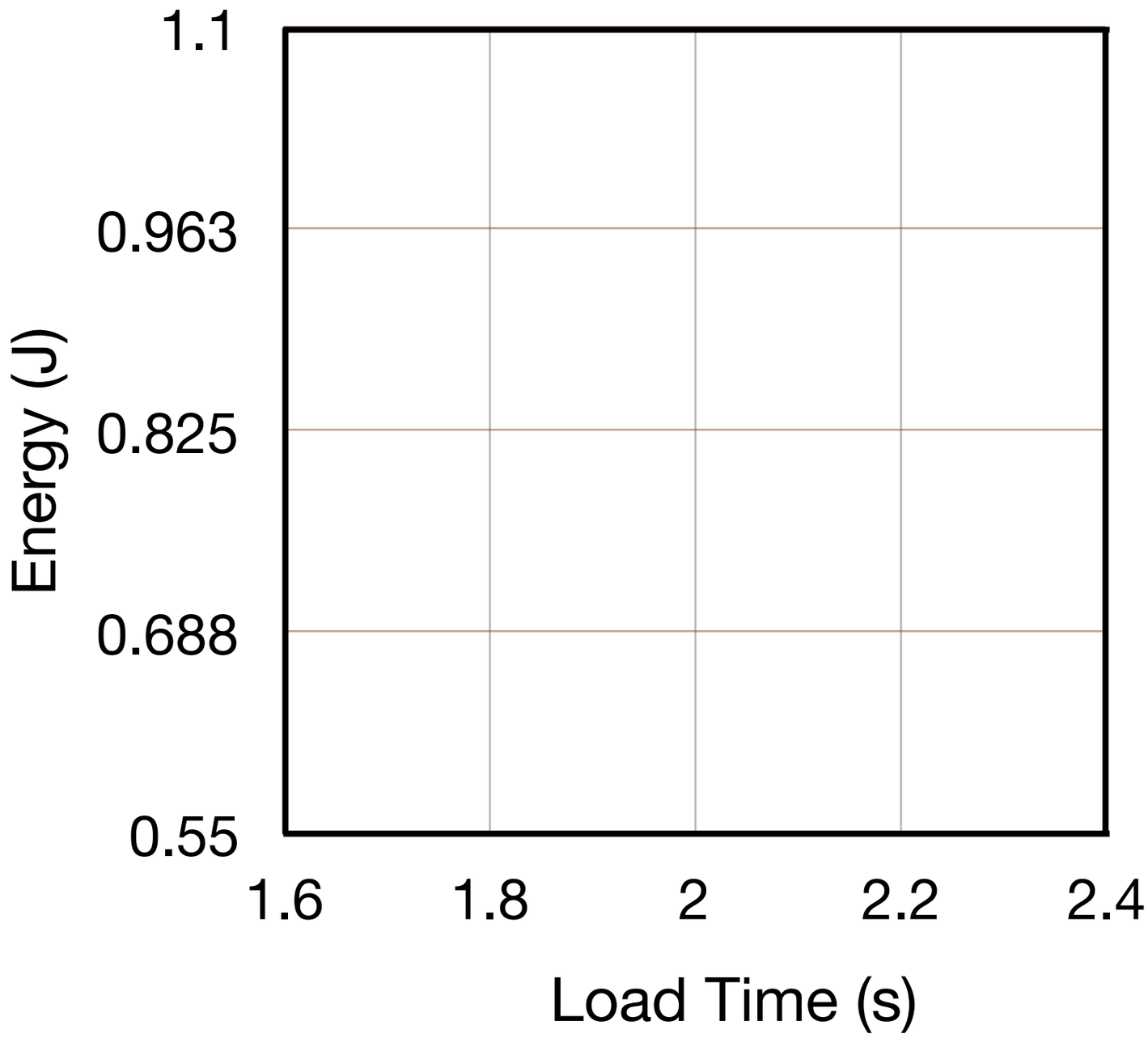

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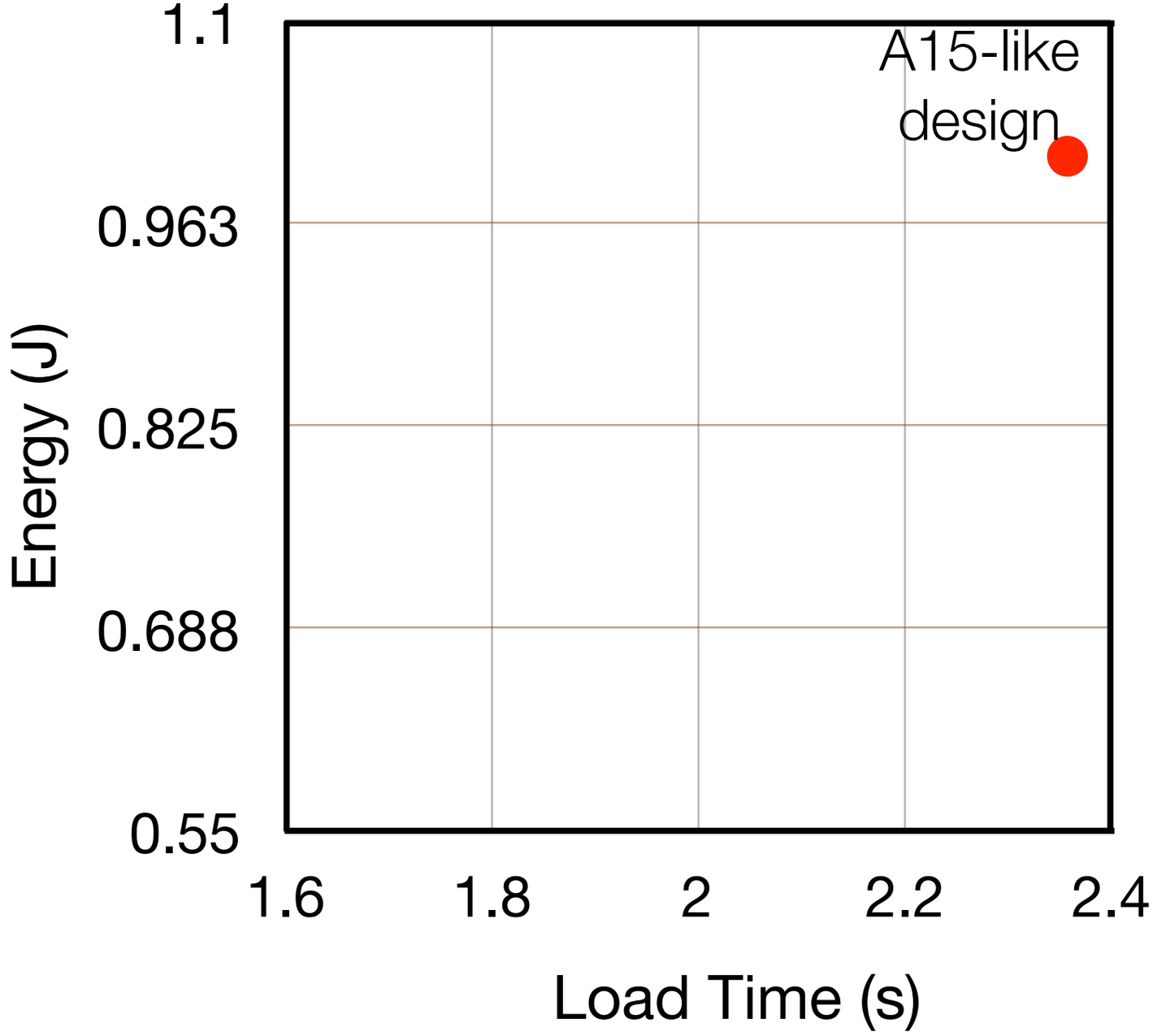

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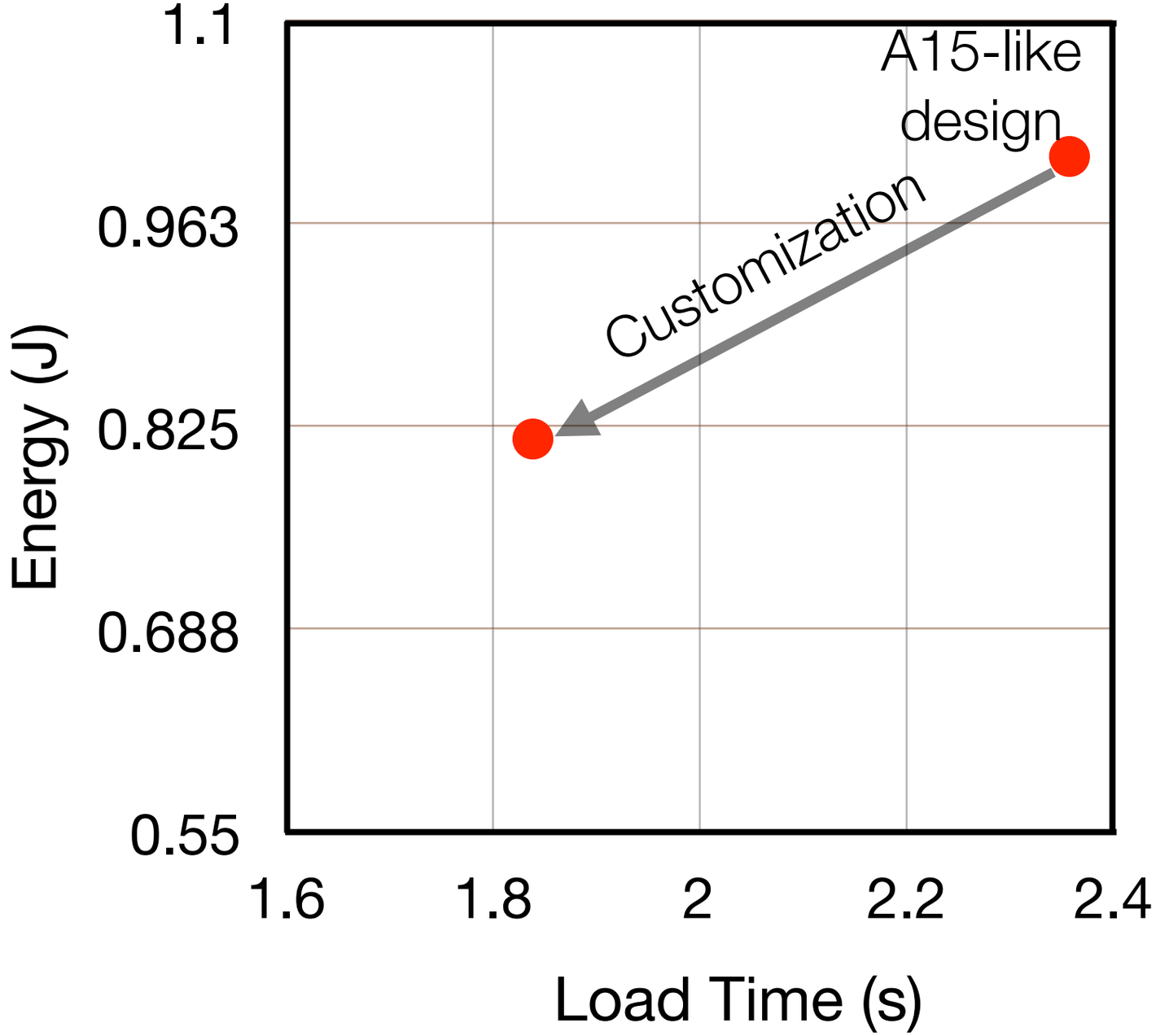

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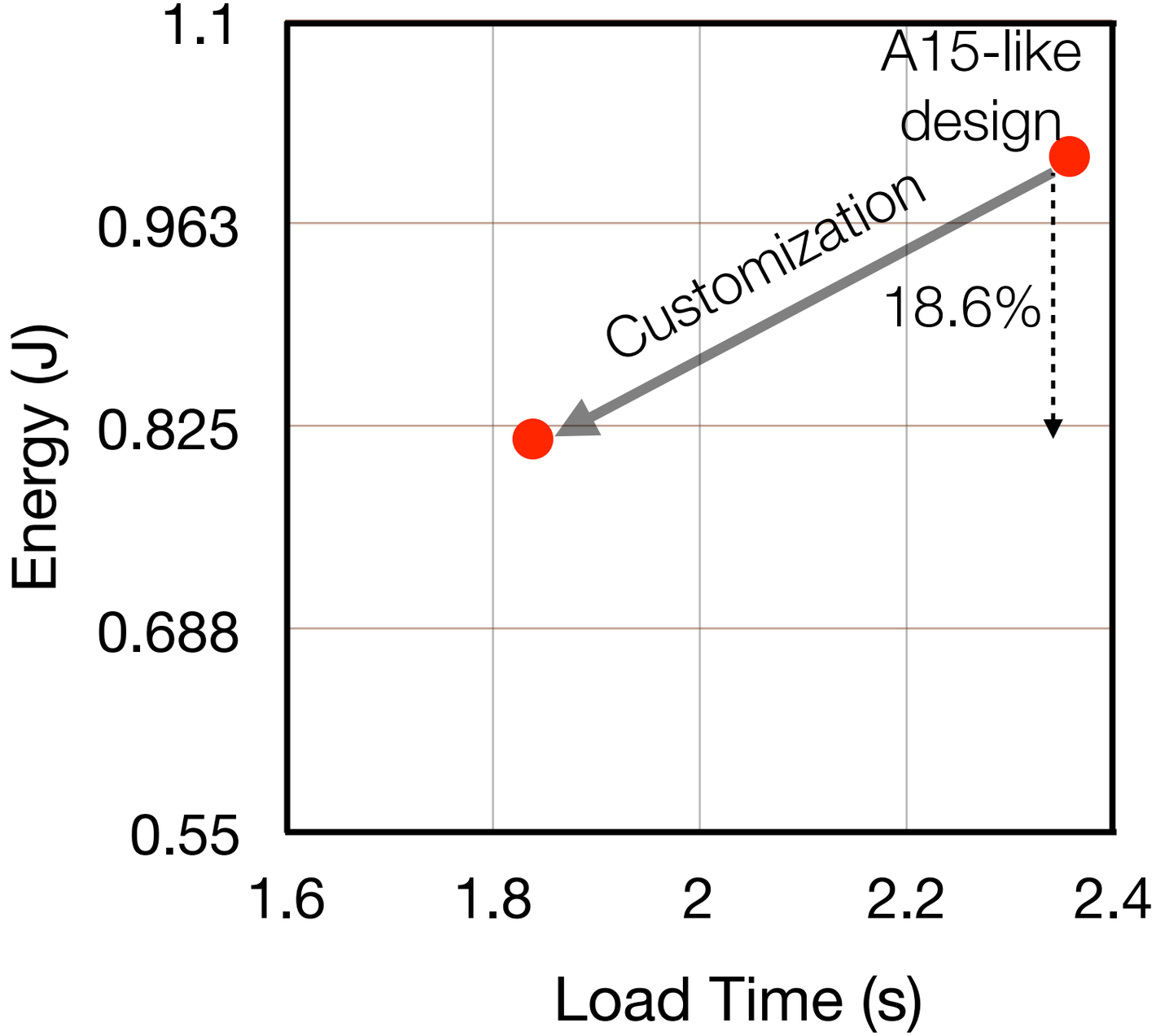

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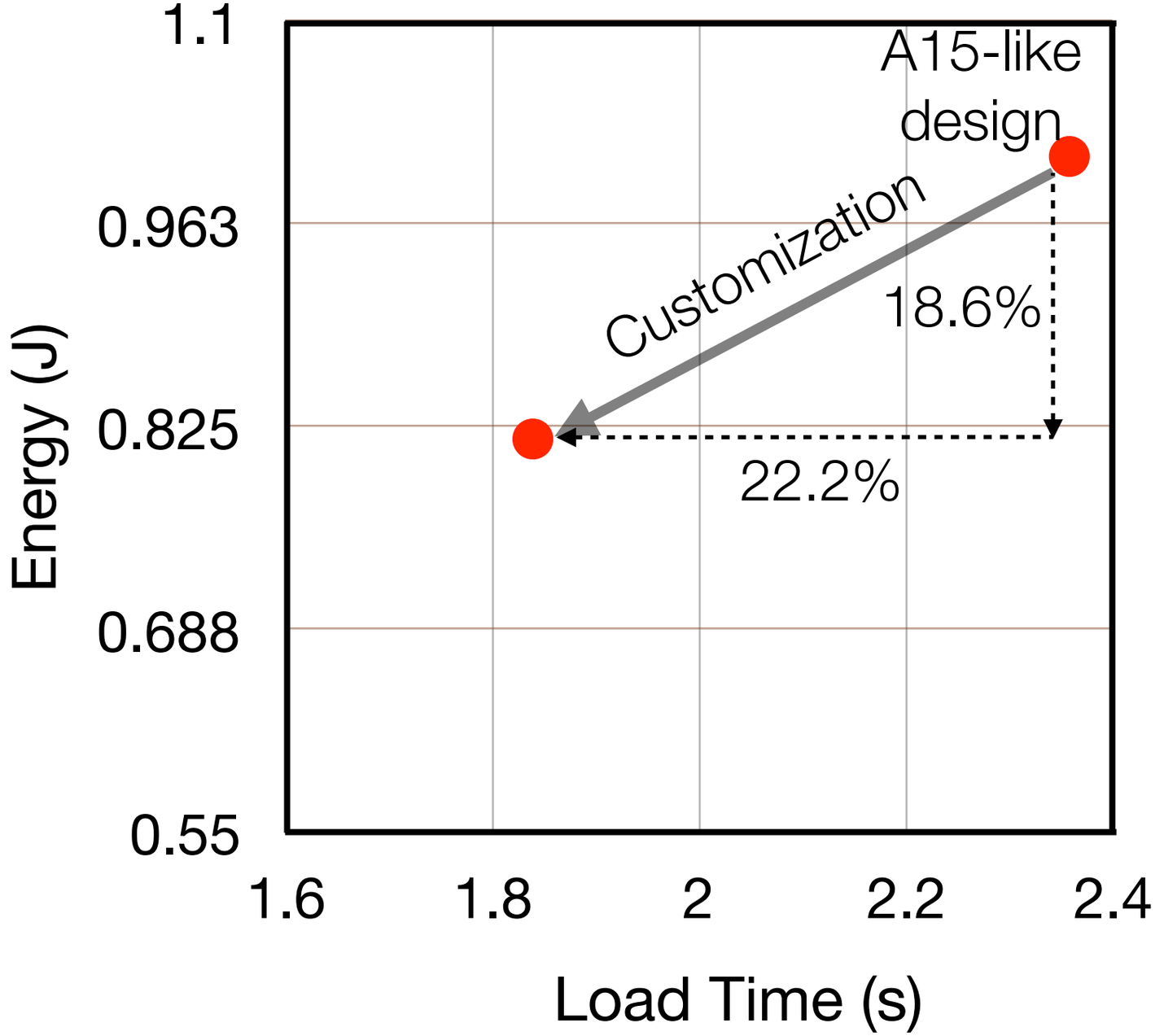

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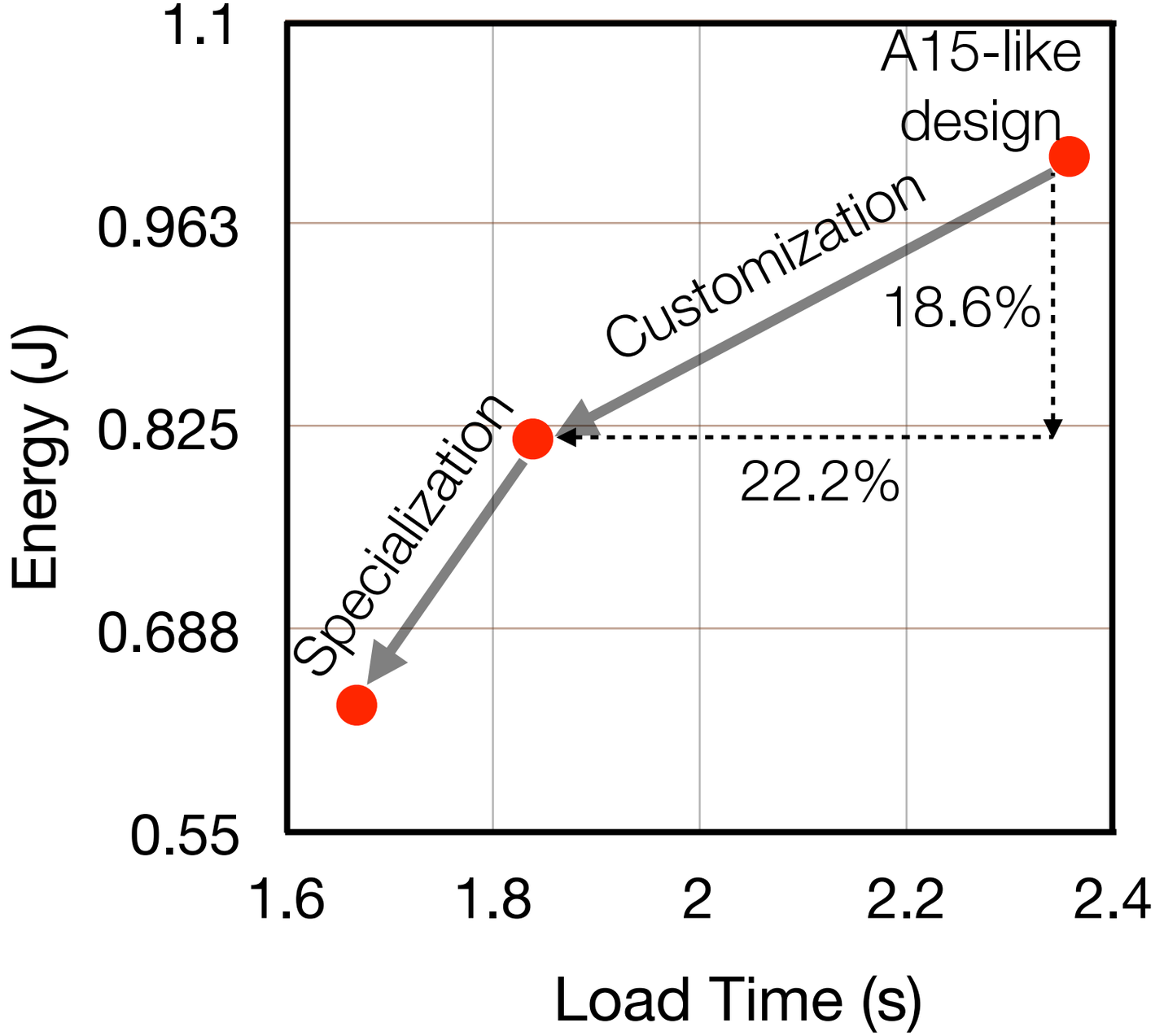

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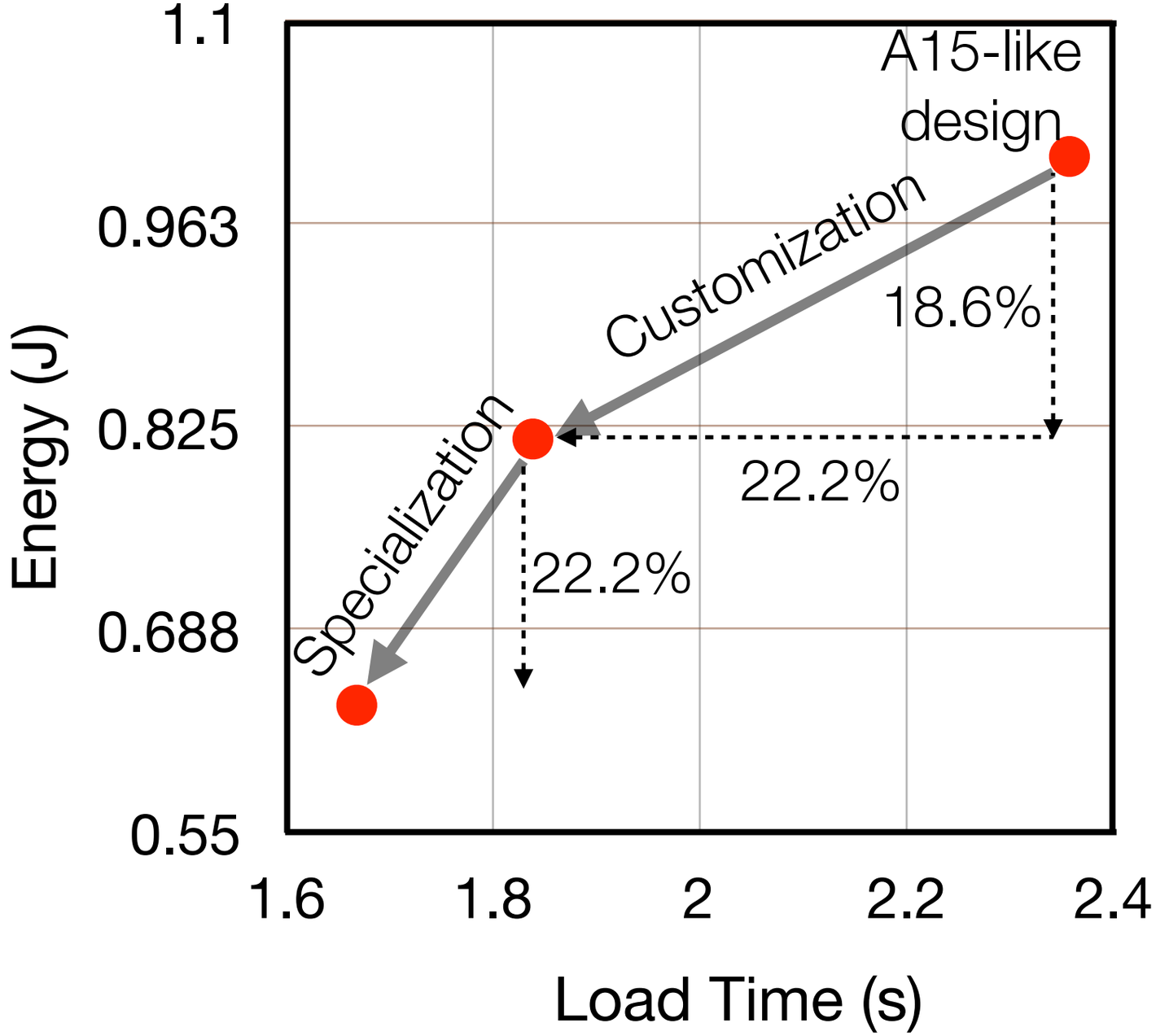

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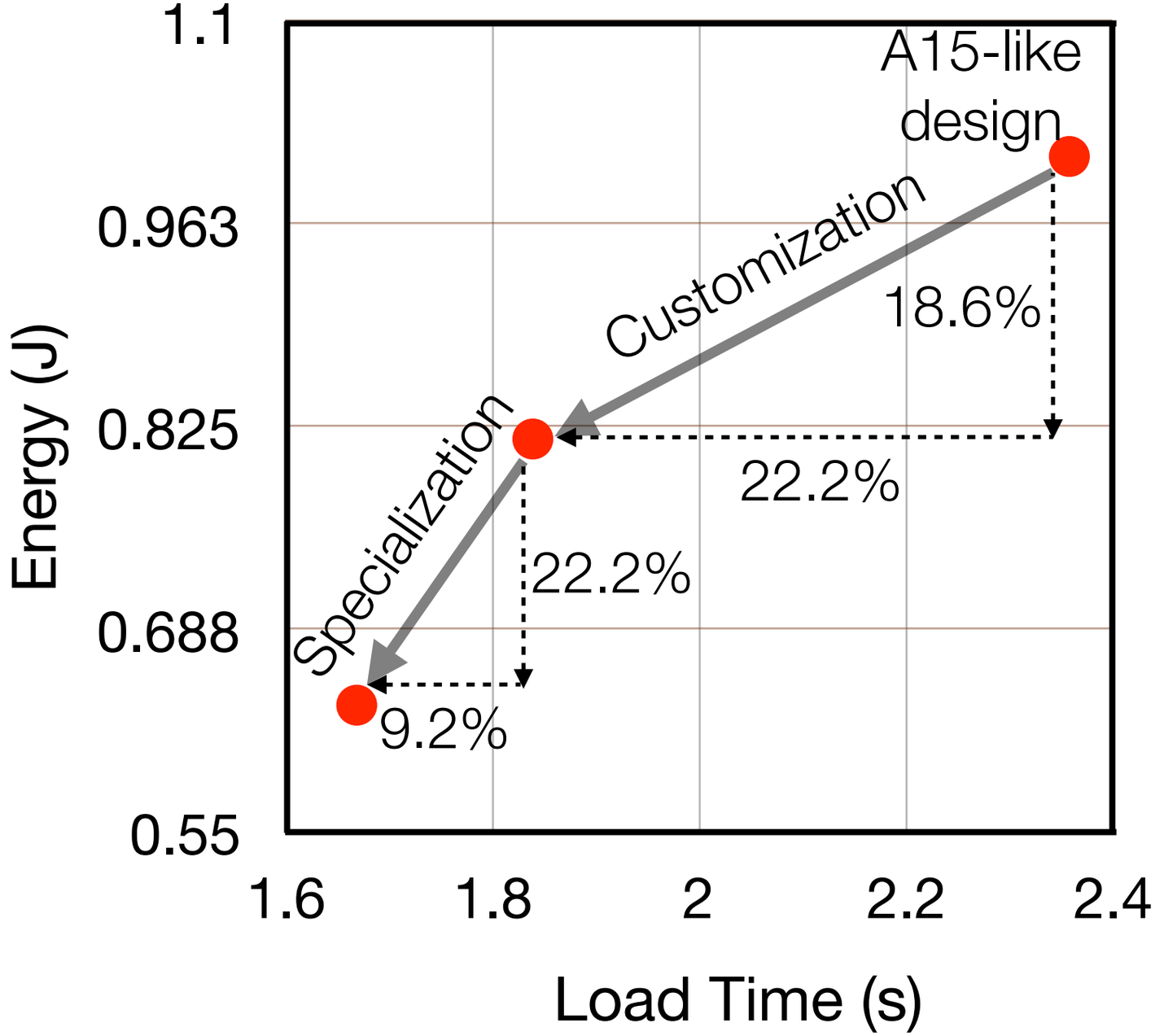

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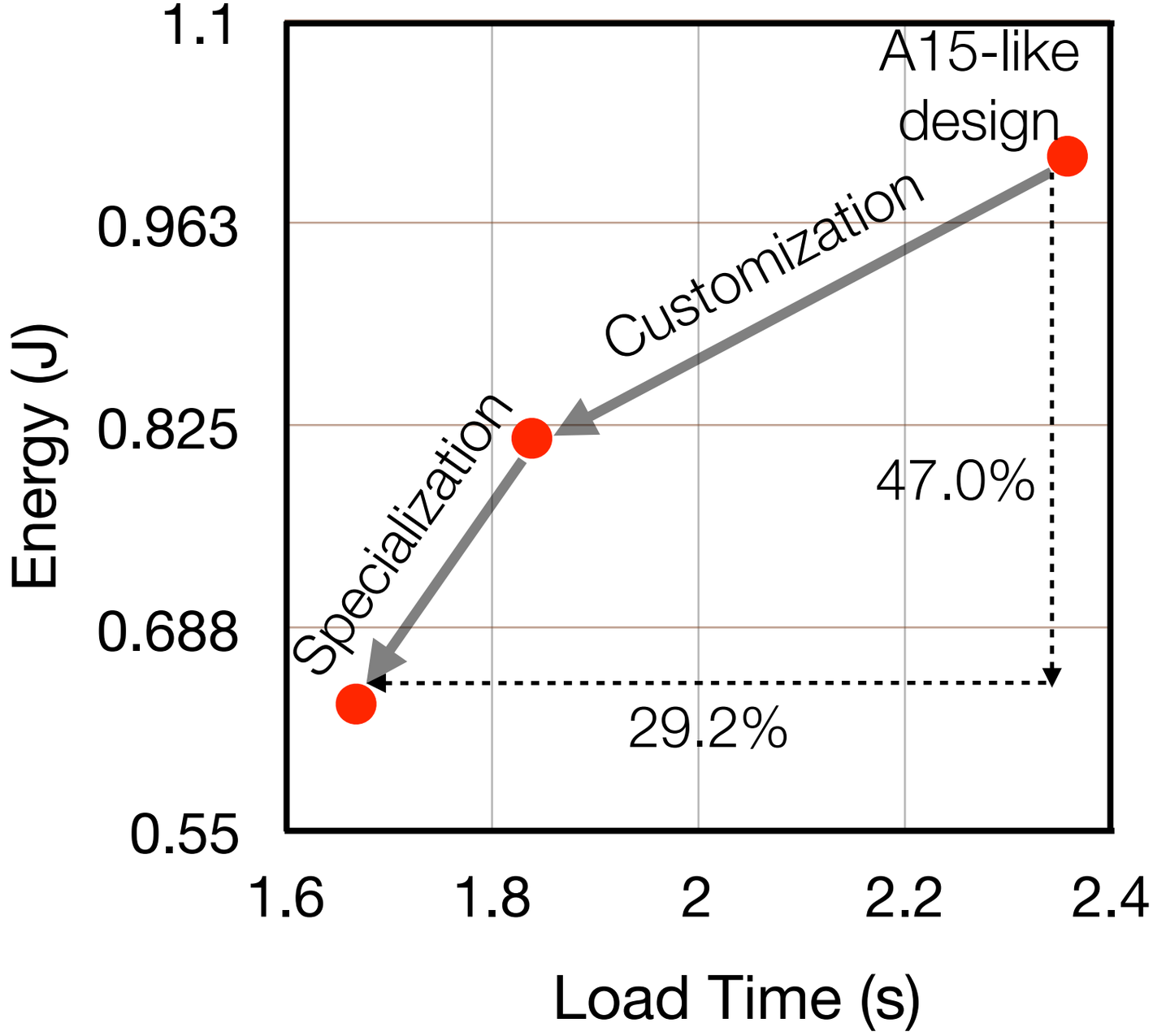
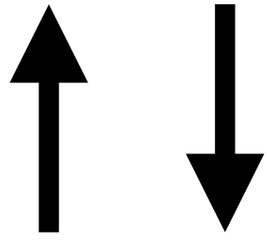
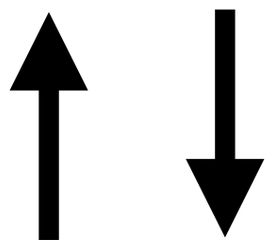


Retrospective: Three Principles Learnt

Application



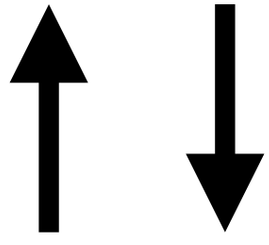
Runtime



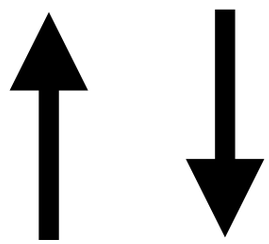
Architecture

Retrospective: Three Principles Learnt

Application



Runtime

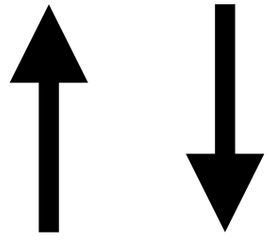


Architecture

- General-purpose vs. Specialization

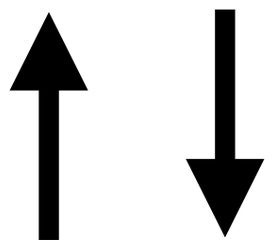
Retrospective: Three Principles Learnt

Application



Runtime

- Exploiting Application Diversity



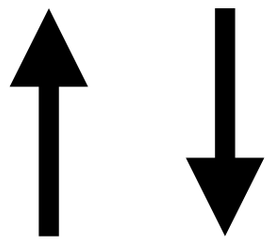
Architecture

- General-purpose vs. Specialization

Retrospective: Three Principles Learnt

Application

- Empowering Web Developers



Runtime

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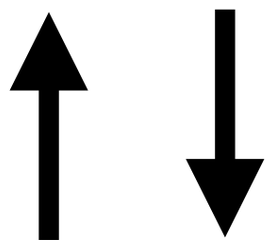


Architecture

- General-purpose vs. Specialization

The Web Evolution

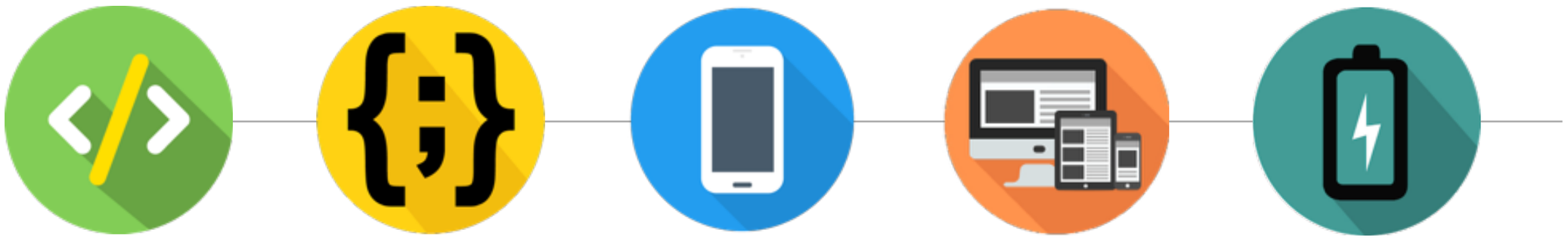
1990
HTML

1996
JavaScript

2008
Mobile Web

2012
Responsive
Web

2016
Watt Wise Web



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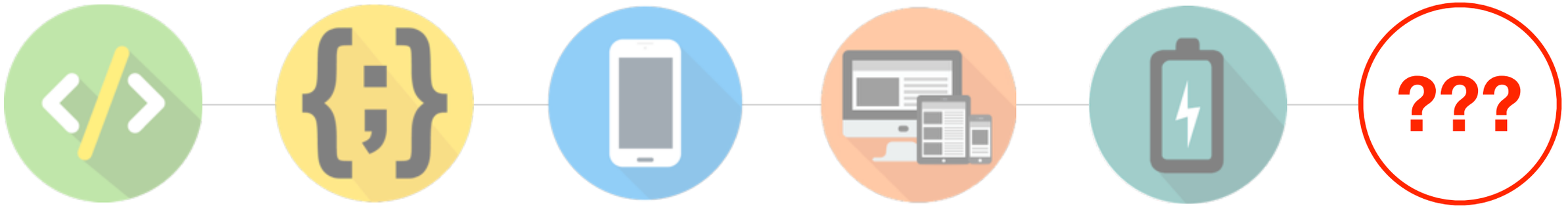


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Thu, March 14


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Thu, March 14


Samsung
SMART TV
Smart Interaction
Smart Content
Smart Evolution


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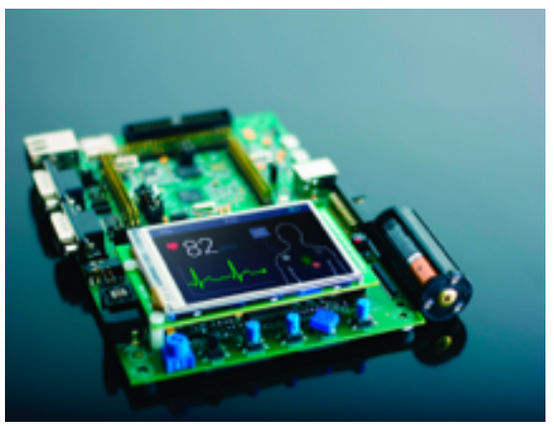
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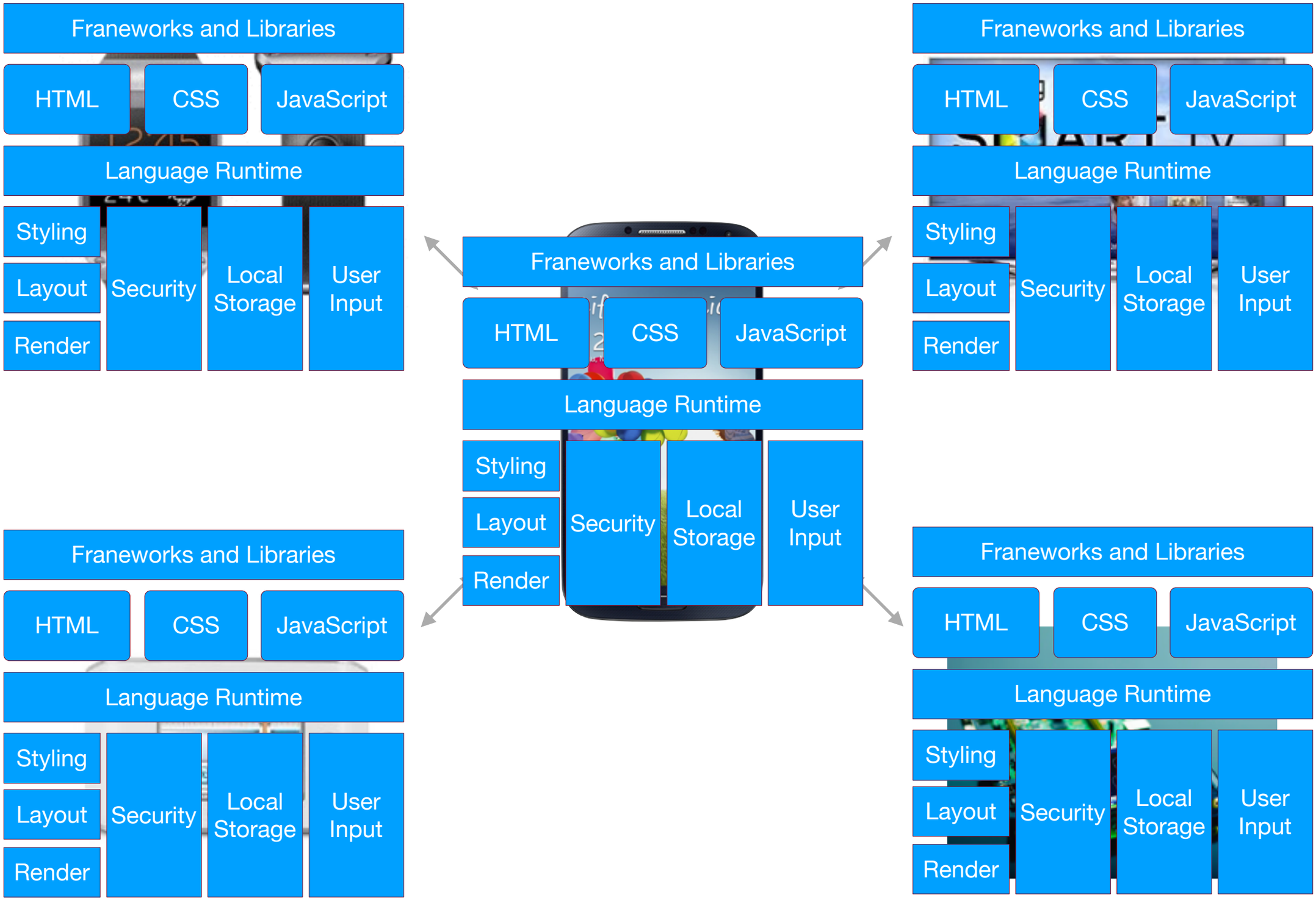
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Thank you!

Future Web	[**ACM Queue**] Yuhao Zhu, Vijay Janapa Reddi, "The Red future of Mobile Web Computing"
GreenWeb	[**PLDI 2016**] Yuhao Zhu, Vijay Janapa Reddi, "GreenWeb: Language Extensions for Energy-Efficient Mobile Web Computing"
WebRT	[**HPCA 2015**] Yuhao Zhu, Matthew Halpern, Vijay Janapa Reddi, "Event-Based Scheduling for Energy-Efficient QoS (eQoS) in Mobile Web Applications"
	[**HPCA 2013**] Yuhao Zhu, Vijay Janapa Reddi, "High-Performance and Energy-Efficient Mobile Web Browsing on Big/Little Systems"
	[**CAL 2012**] Yuhao Zhu, Aditya Srikanth, Jingwen Leng, Vijay Janapa Reddi, "Exploiting Webpage Characteristics for Energy-Efficient Mobile Web Browsing" (**Best of CAL**)
WebCore	[**ISCA 2014**] Yuhao Zhu, Vijay Janapa Reddi, "WebCore: Architectural Support for Mobile Web Browsing"
Motivational Studies	[**IEEE MICRO 2015**] Yuhao Zhu, Matthew Halpern, Vijay Janapa Reddi, "The Role of the CPU in Energy-Efficient Mobile Web Browsing"
	[**HPCA 2016**] Matthew Halpern, Yuhao Zhu, Vijay Janapa Reddi, "Mobile CPU's Rise to Power: Quantifying the Impact of Generational Mobile CPU Design Trends on Performance, Energy, and User Satisfaction"

Server Microarch	[**MICRO 2015**] Yuhao Zhu, Daniel Richins, Matthew Halpern, Vijay Janapa Reddi, "Microarchitectural Implications of Event-driven Server-side Web Applications" (**Top Picks Honorable Mention**)
GPGPU & IP Routing Architecture	[**DAC 2011**] Yuhao Zhu, Yangdong Deng, Yubei Chen, "Hermes: An Integrated CPU/GPU Microarchitecture for IP Routing."
	[**DAC 2010**] Bo Wang, Yuhao Zhu, Yangdong Deng, "Distributed Time, Conservative Parallel Logic Simulation on GPUs."
	[**TODAES 2011**] Yuhao Zhu, Bo Wang, Yangdong Deng, "Massively Parallel Logic Simulation with GPUs."
Tools	[**ISPASS 2015**] Matthew Halpern, Yuhao Zhu, Ramesh Peri, and Vijay Janapa Reddi, "Mosaic: Cross-platform User-interaction Record and Replay for the Fragmented Android Ecosystem."
Reliability	[**IRPS 2014**] Chen Zhou, Xiaofei Wang, Weichao Xu, Yuhao Zhu, Vijay Janapa Reddi, Chris Kim, "Estimation of Instantaneous Frequency Fluctuation in a Fast DVFS Environment Using an Empirical BTI Stress-Relaxation Model."

Coursework

Name	Instructor	Semester	SUP	Grade
COMPILERS	Keshav Pingali	Fall 2010		A
ADV EMBED MICROCONTROL SYS	Mark McDermott	Spring 2011		A-
MEMORY MANAGEMENT	Kathryn McKinley	Spring 2011	Y	A
VLSI I	Jacob Abraham	Fall 2011		A-
COMP ARCH: PARALLISM/LOCLTY	Mattan Erez	Fall 2011		A
MICROARCHITECTURE	Yale Patt	Spring 2012		B
DYNAMIC COMPILATION	Vijay Janapa Reddi	Spring 2012		A-
COMP PERF EVAL/BENCHMARKING	Lizy John	Fall 2012		B+
PARALLEL COMP ARCHITECTURE	Derek Chiou	Spring 2013		B+
HUMAN COMPUT & CROWDSRCING	Matt Lease	Fall 2015	Y	A-