GreenWeb:

Language Extensions for Energy-Efficient Mobile Web Computing

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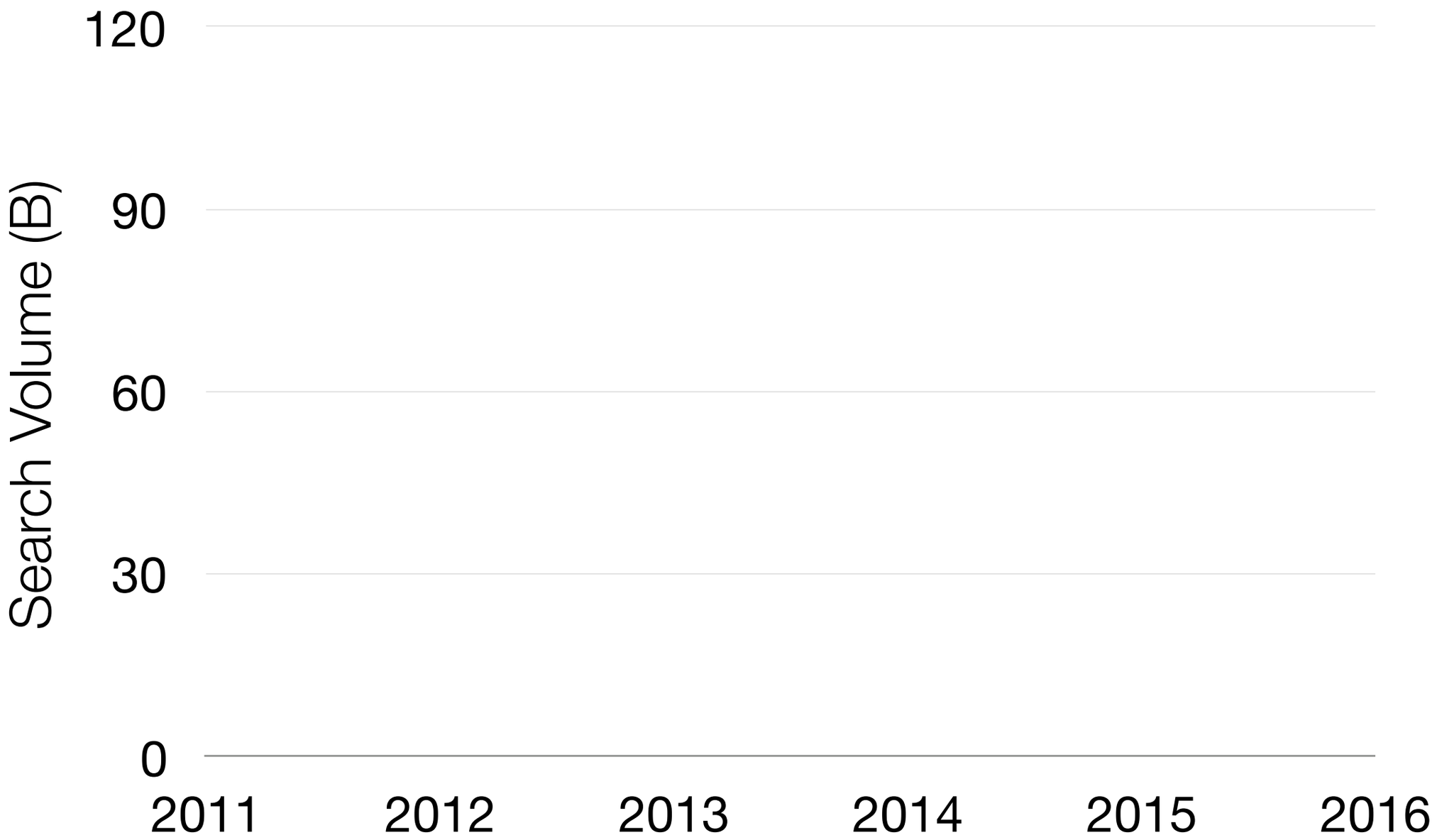
The University of Texas at Austin
with Vijay Janapa Reddi

PLDI 2016

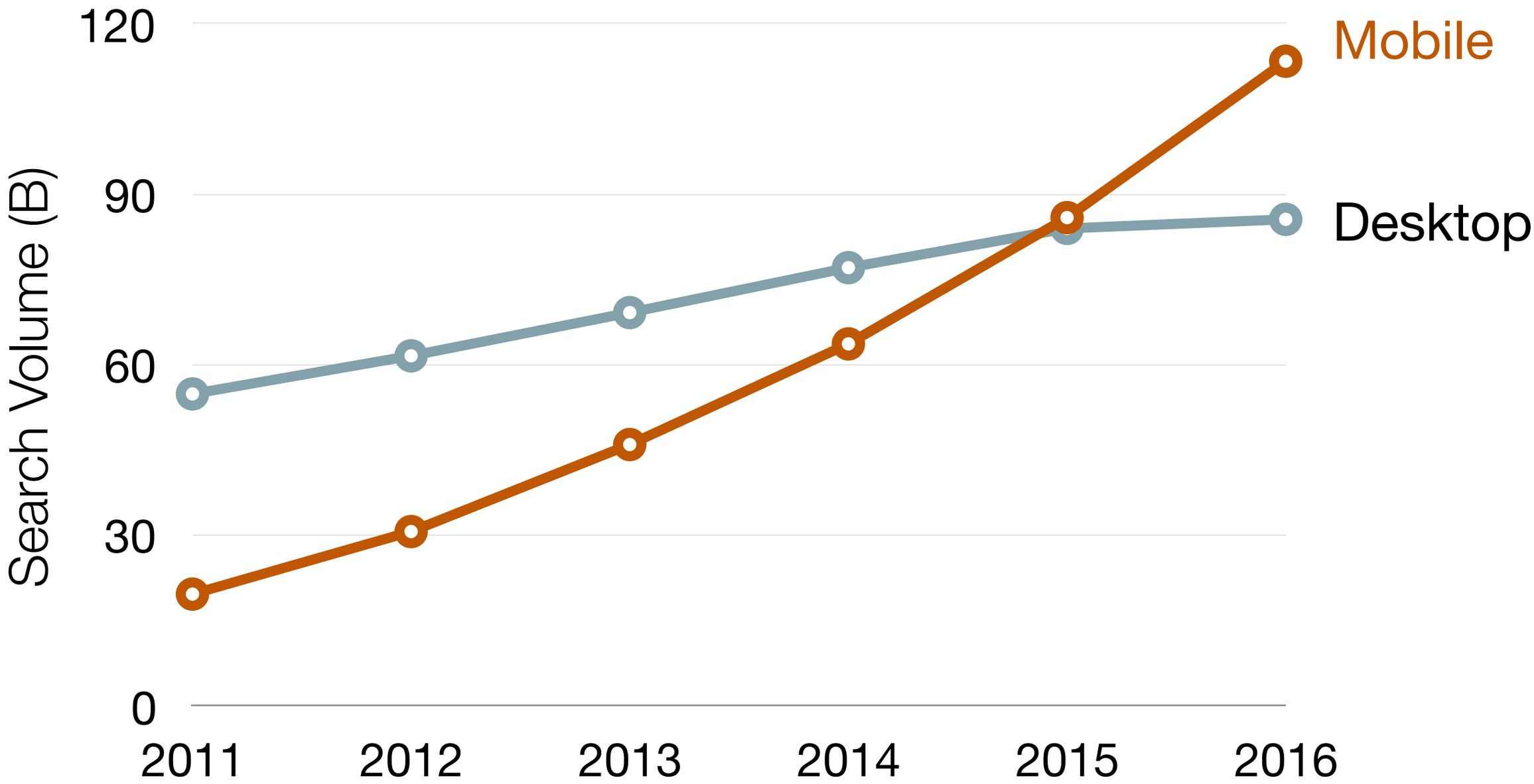
Web: Mobile Overtaking Desktop

Web: Mobile Overtaking Desktop



Source: BIA/Kelsey

Web: Mobile Overtaking Desktop



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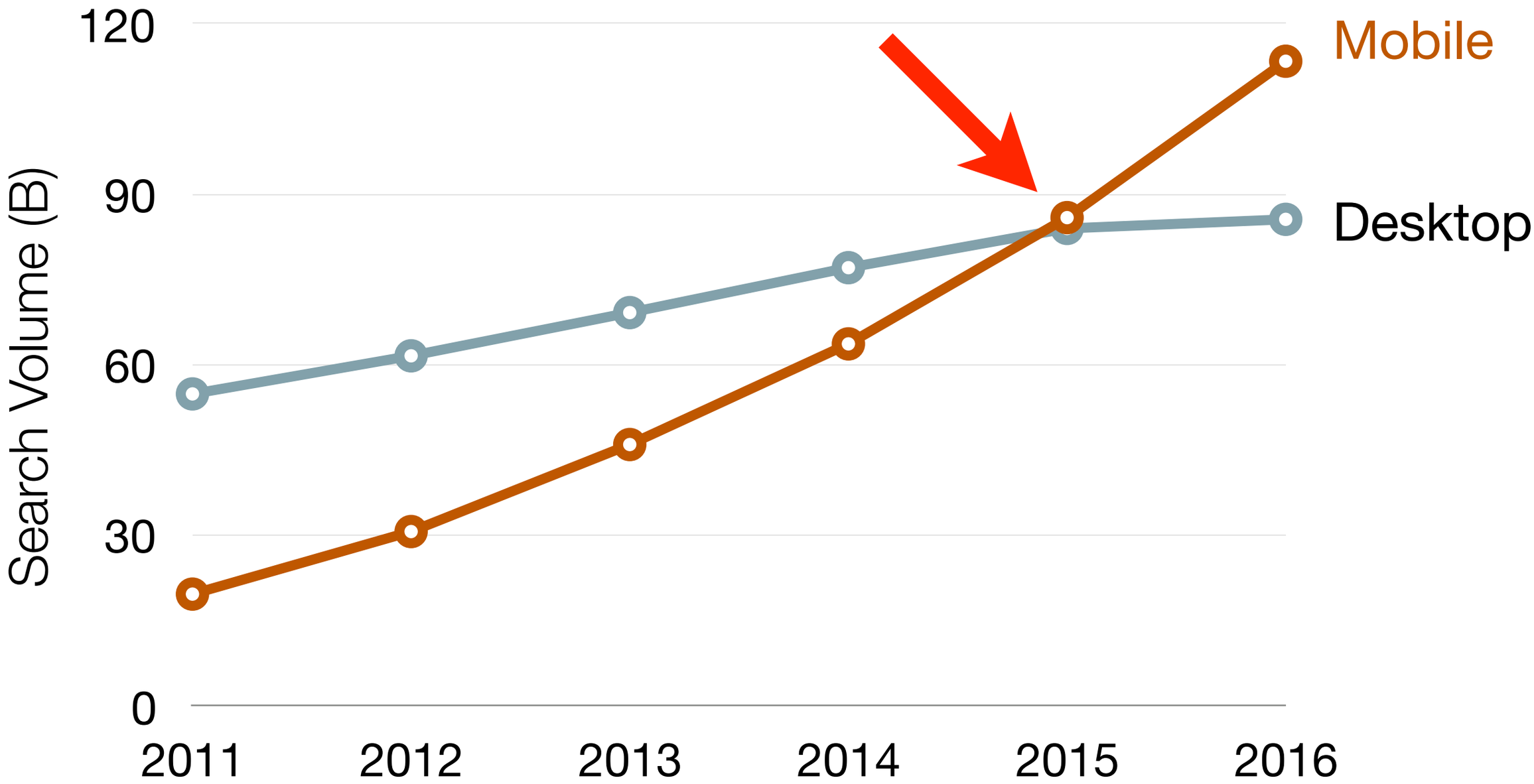


Source: BIA/Kelsey

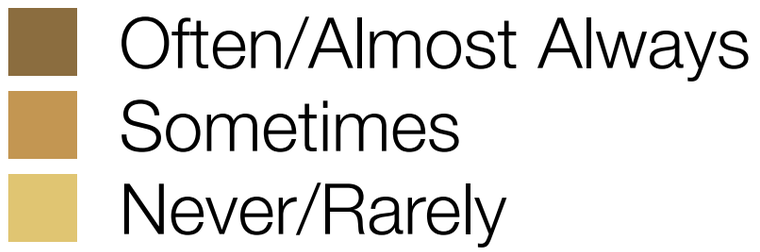
Web ≈ Mobile Web

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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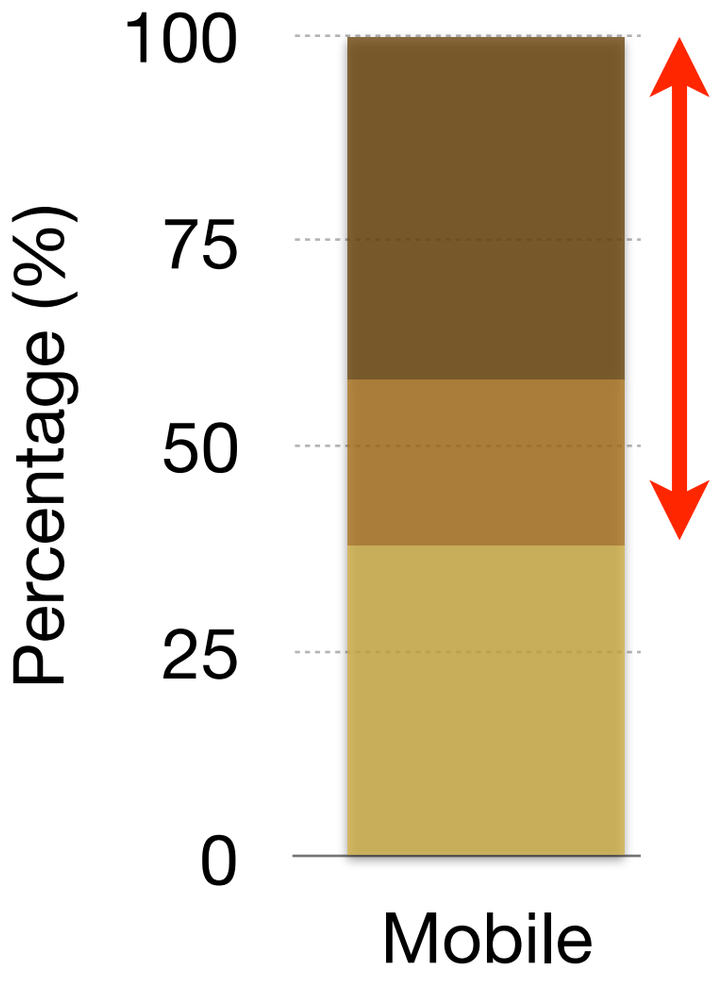
Energy Concern Among Mobile Developers



"My applications have requirements about energy usage."

- Often/Almost Always
- Sometimes
- Never/Rarely

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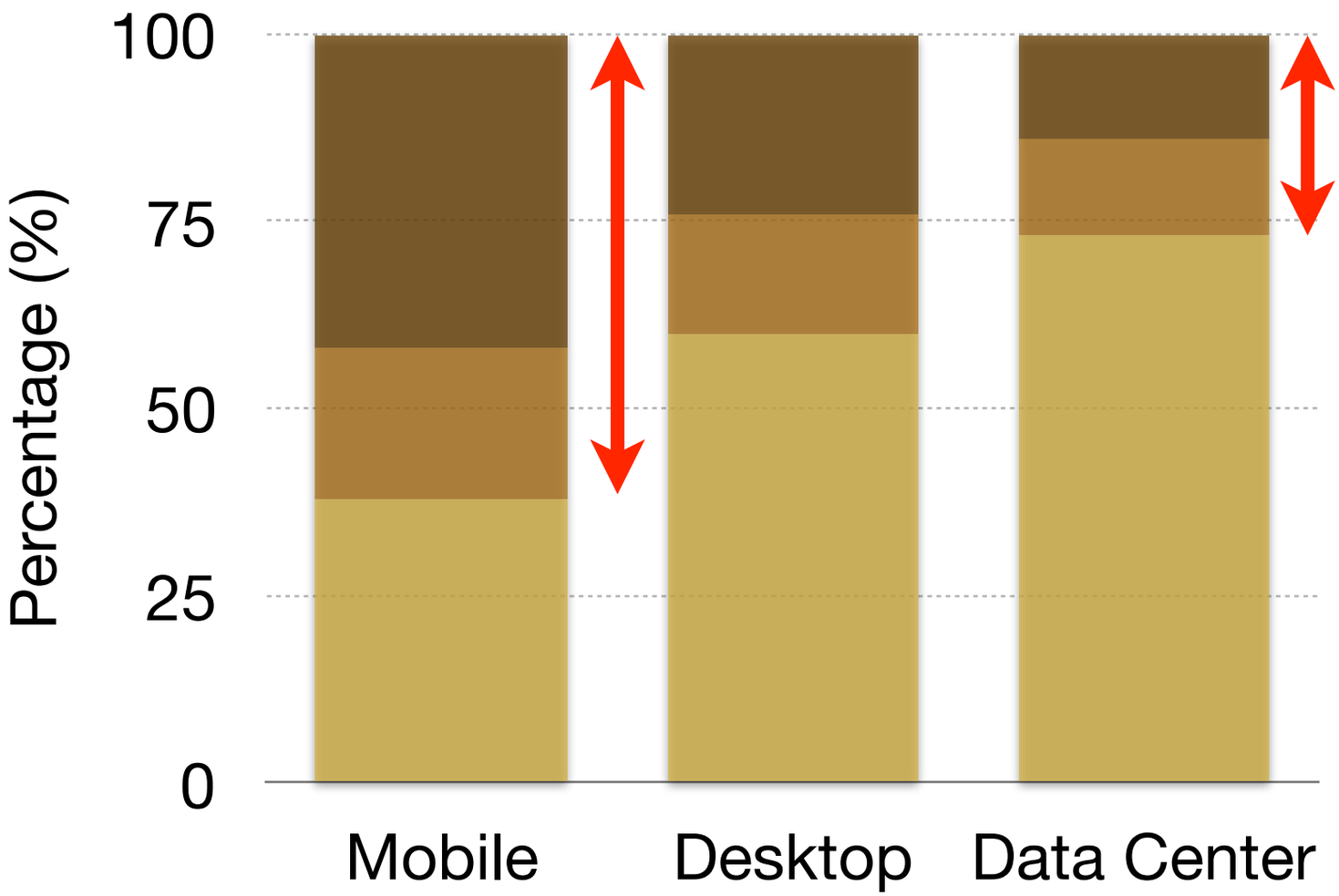
Energy Concern Among Mobile Developers



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Developers are Willing to Make Trade-offs

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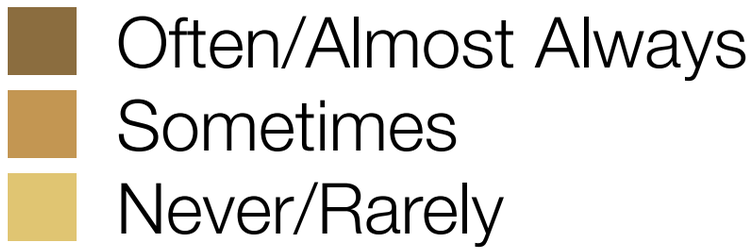
Developers are Willing to Make Trade-offs

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



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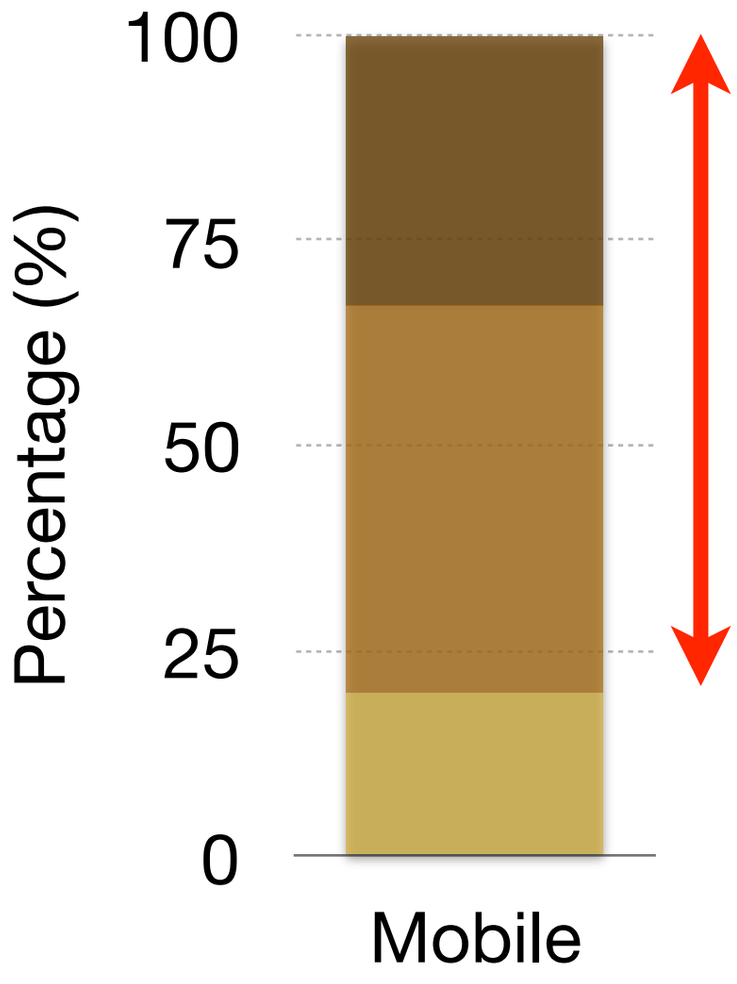

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Often/Almost Always
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Energy-efficiency

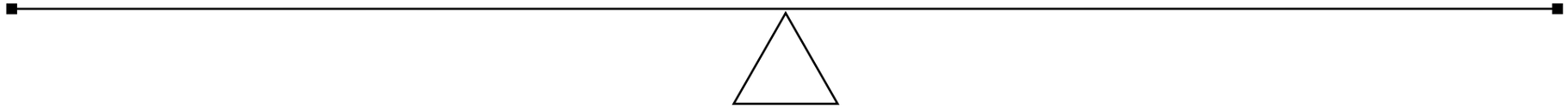
Quality-of-service

Energy-efficiency

Quality-of-service

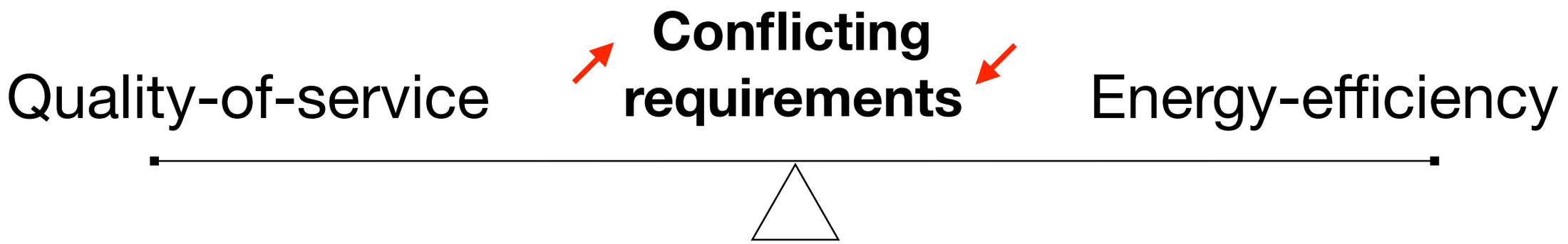
Conflicting requirements

Energy-efficiency



GreenWeb

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



GreenWeb

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

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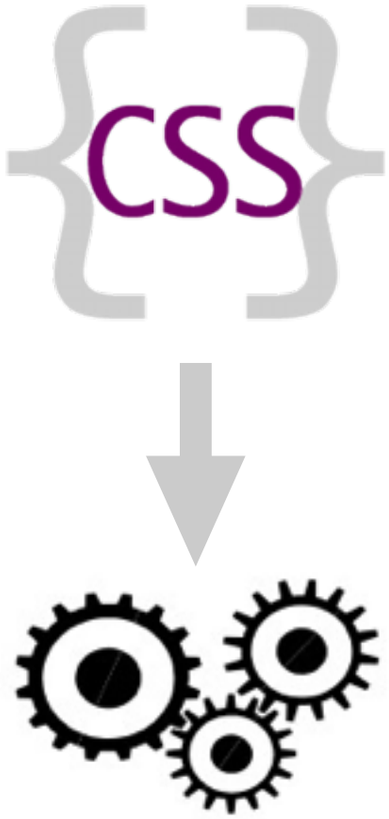
Programming language support for balancing energy-efficiency and QoS in mobile Web computing

GreenWeb: Language for Energy-Efficiency

- **Language abstractions** for expressing QoS

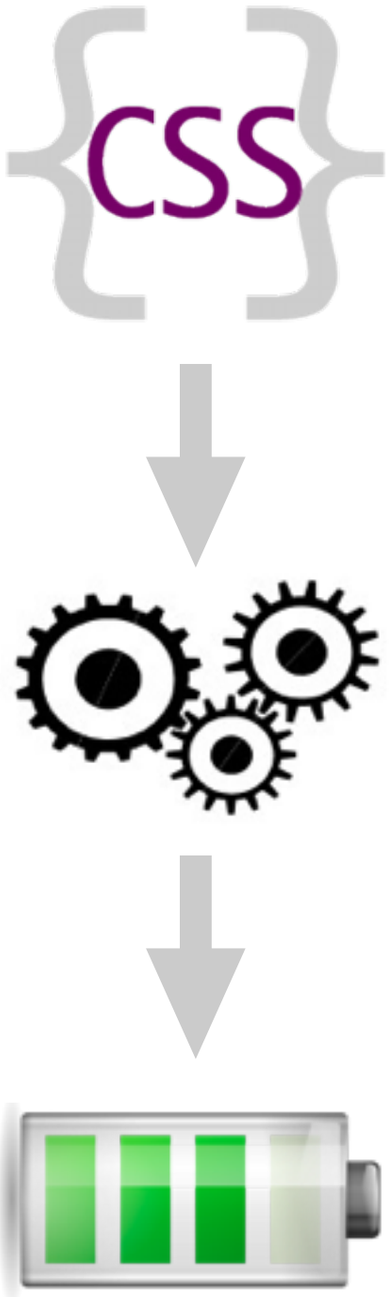
GreenWeb: Language for Energy-Efficiency



- **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

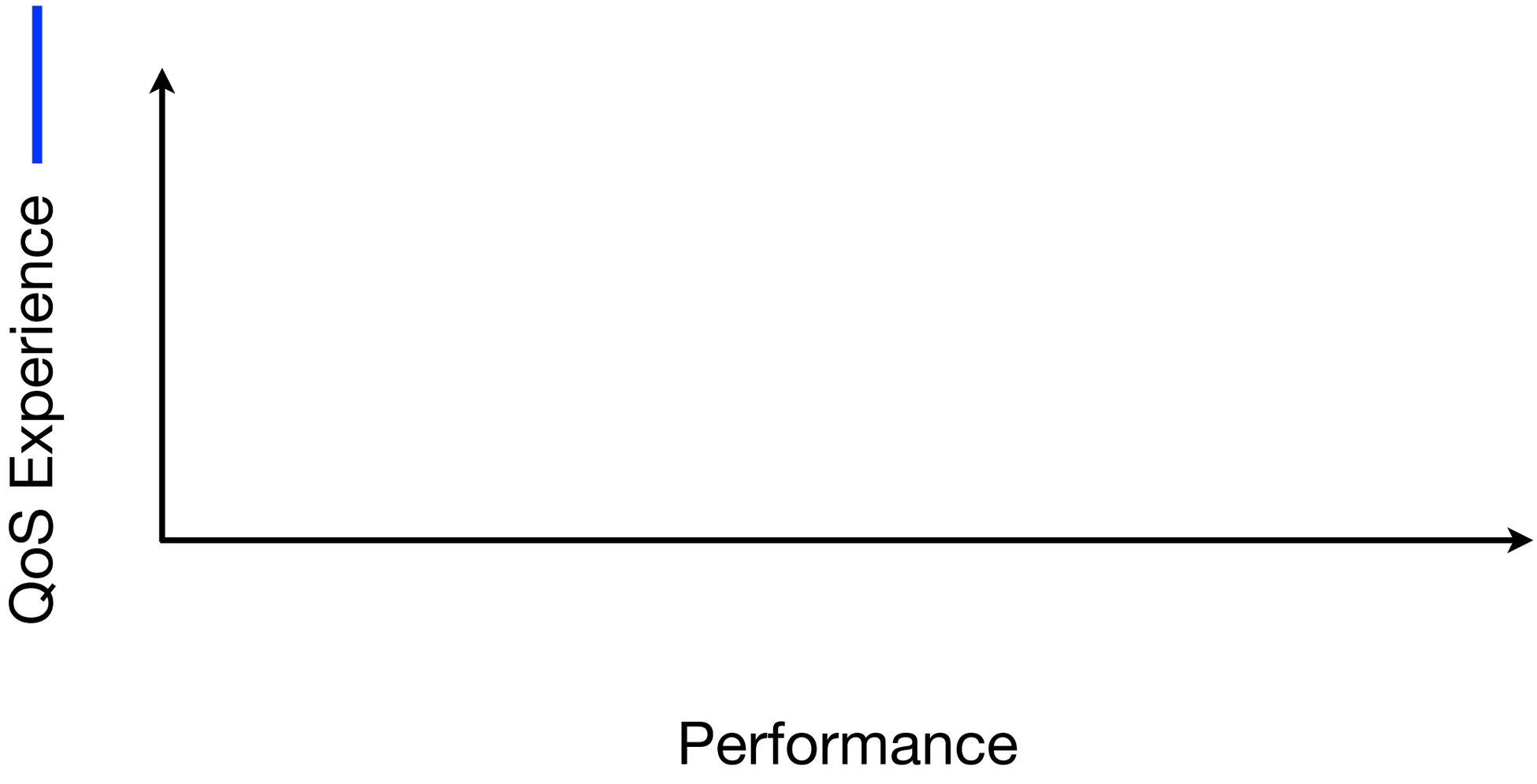
GreenWeb: Language for Energy-Efficiency

- **Language abstractions** for expressing QoS
- Runtime
  the QoS constraints
- Result
  hardware/software implementations

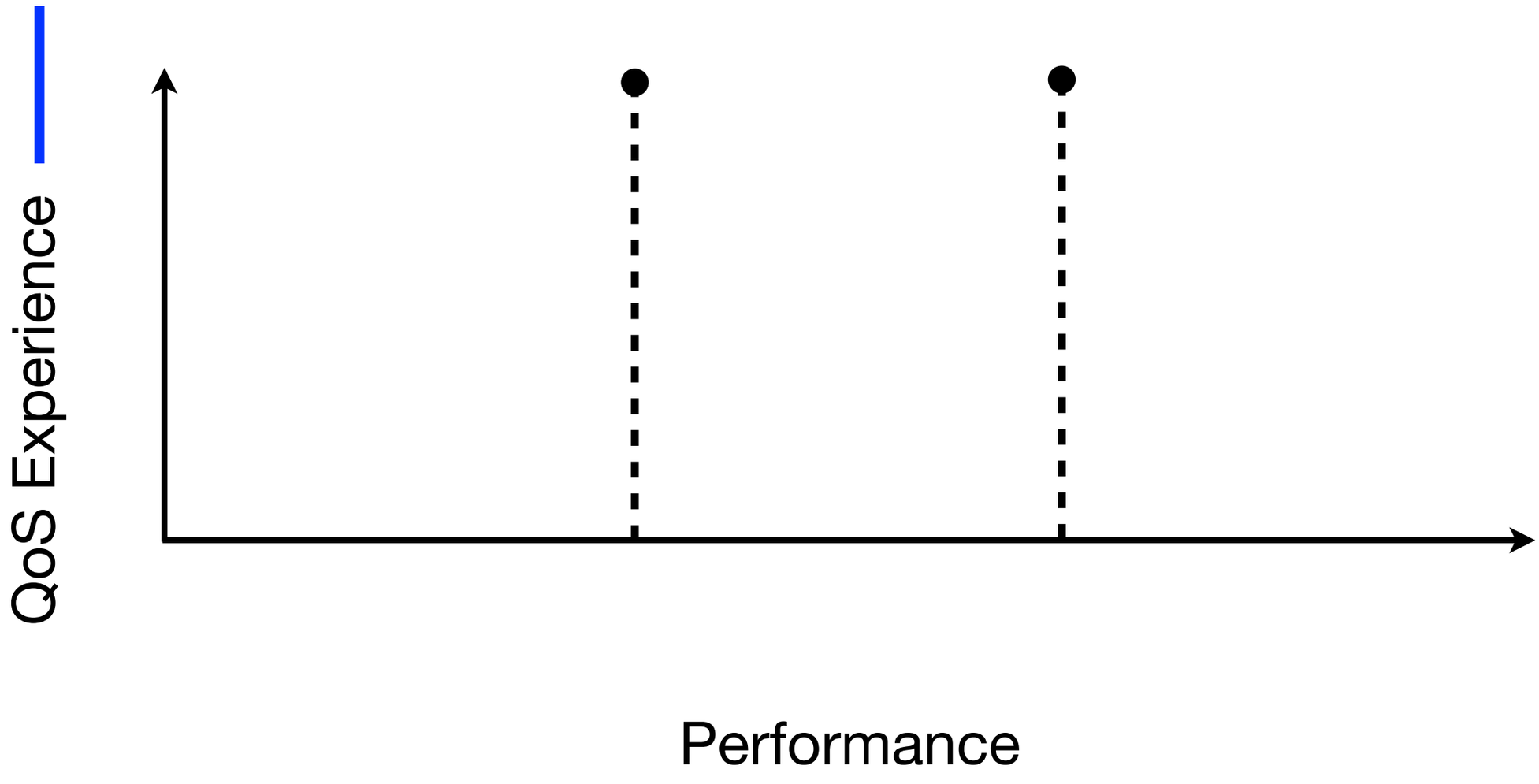
What is QoS in mobile Web?

Understanding Mobile Web QoS

Understanding Mobile Web QoS



Understanding Mobile Web QoS



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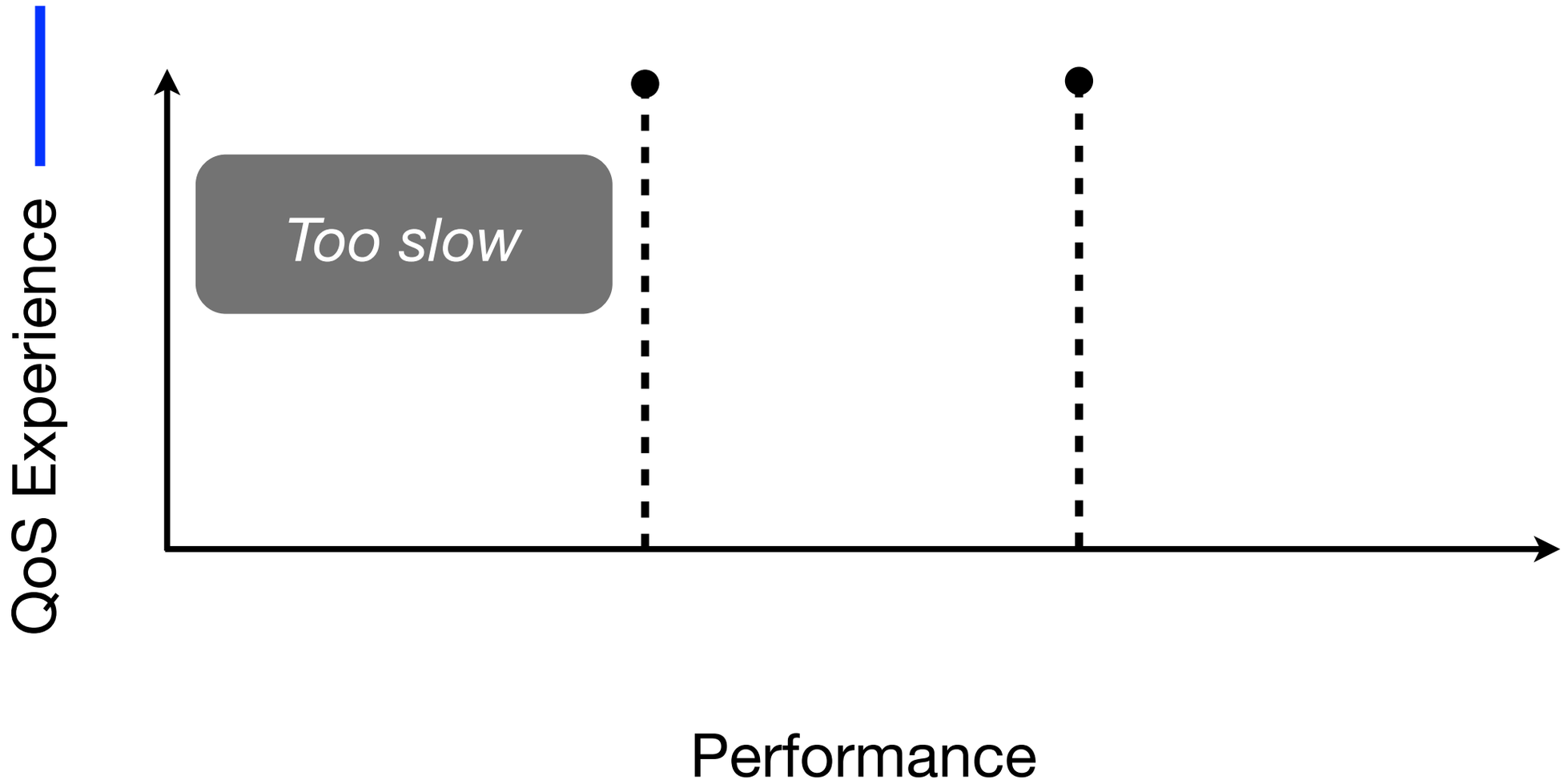

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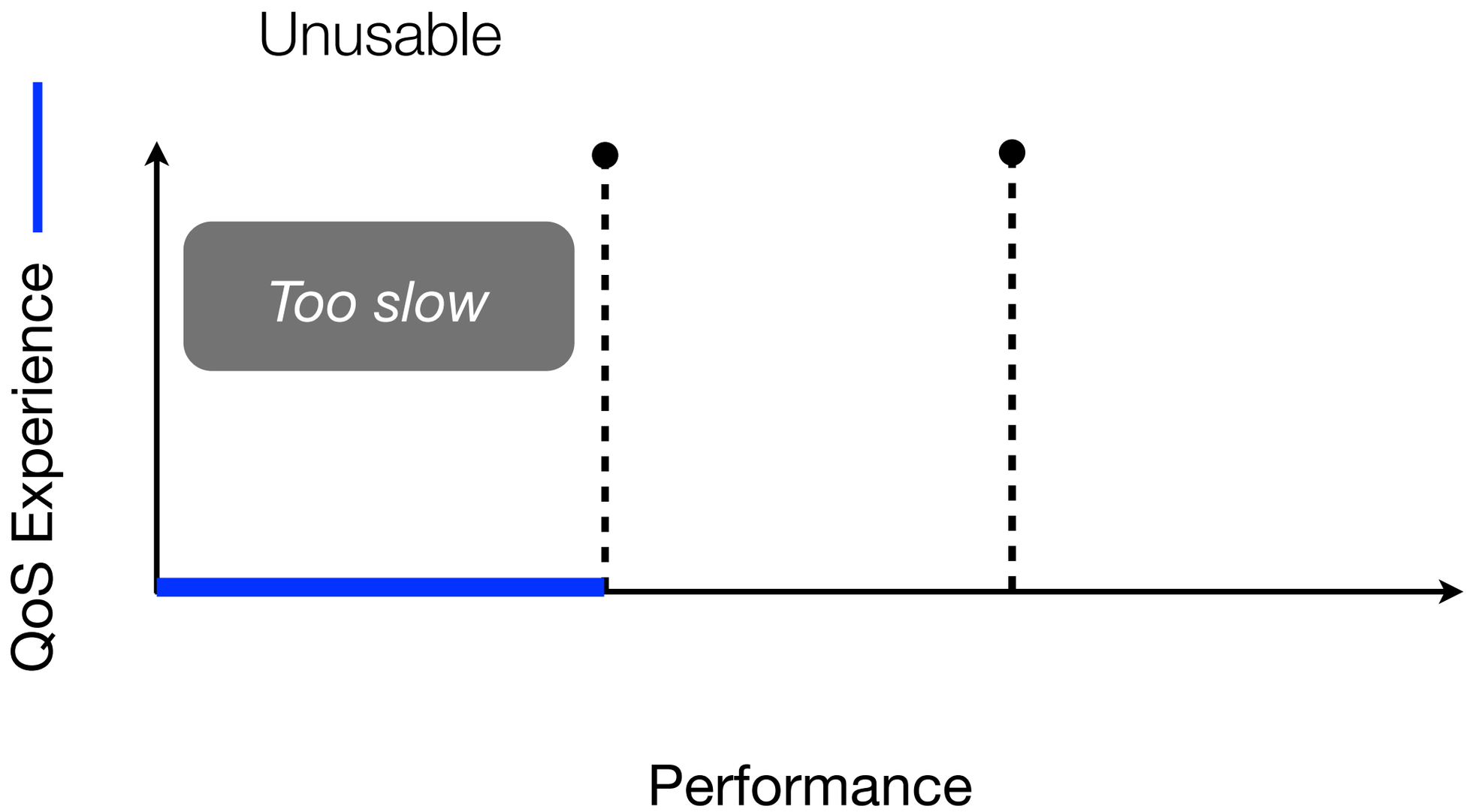

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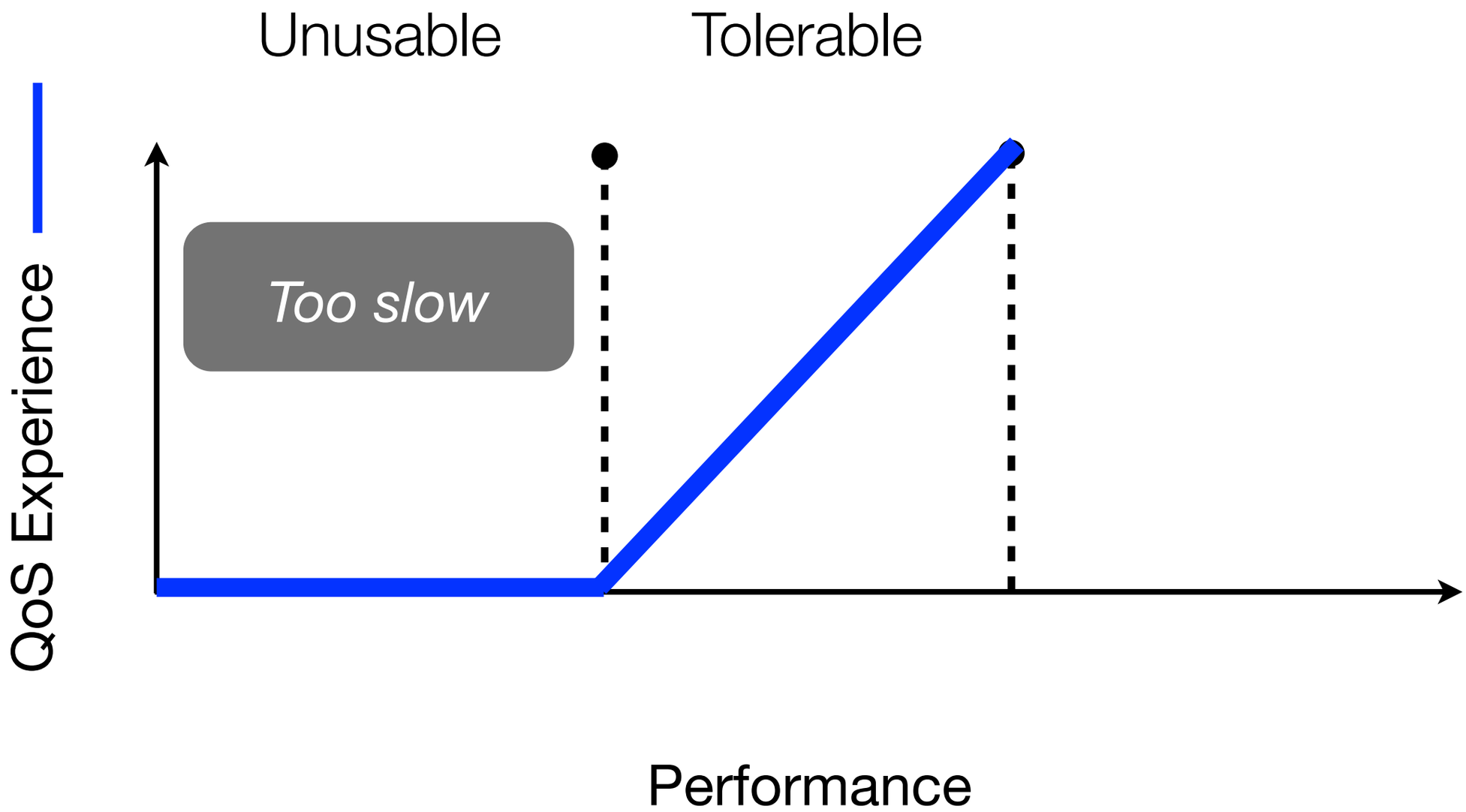

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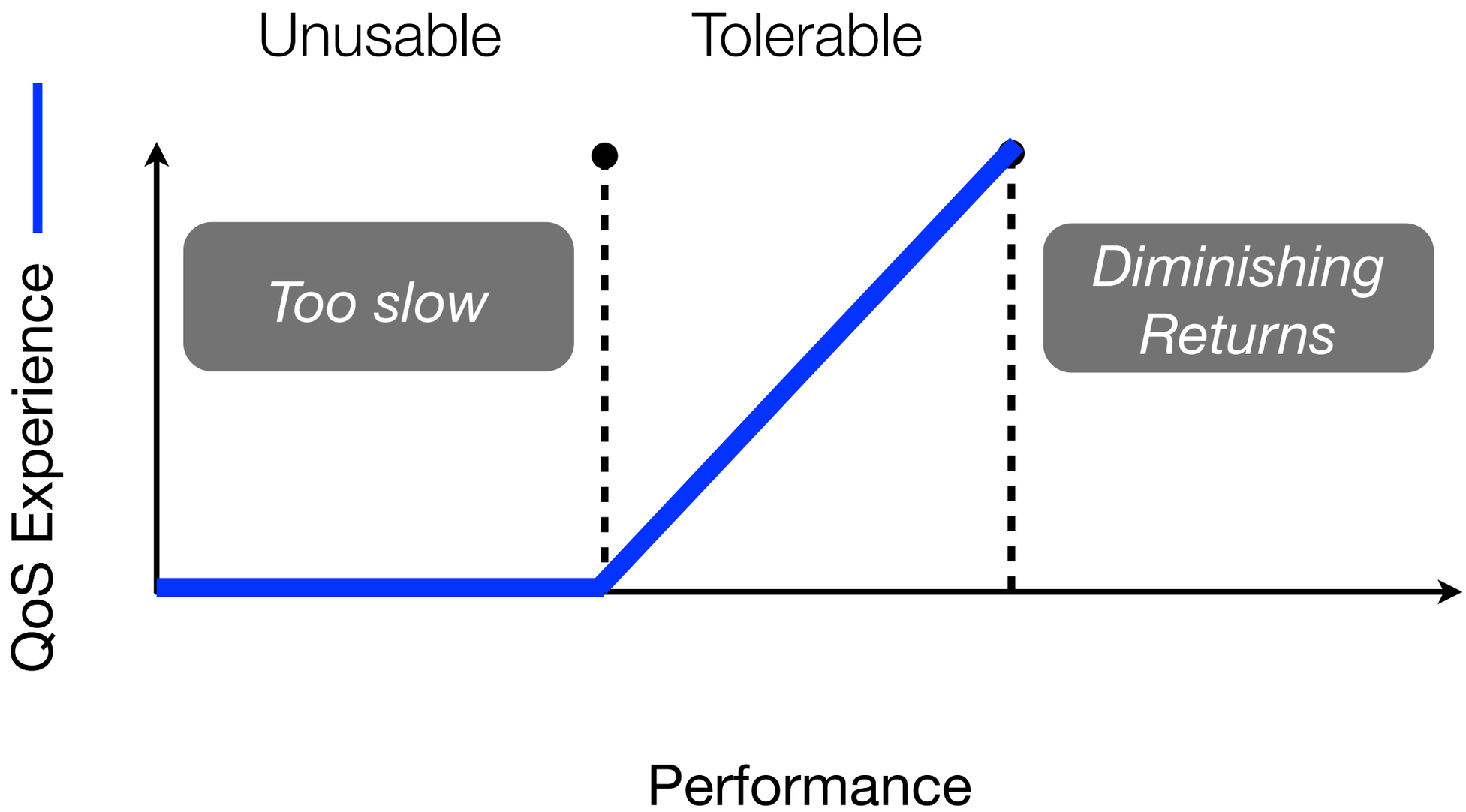

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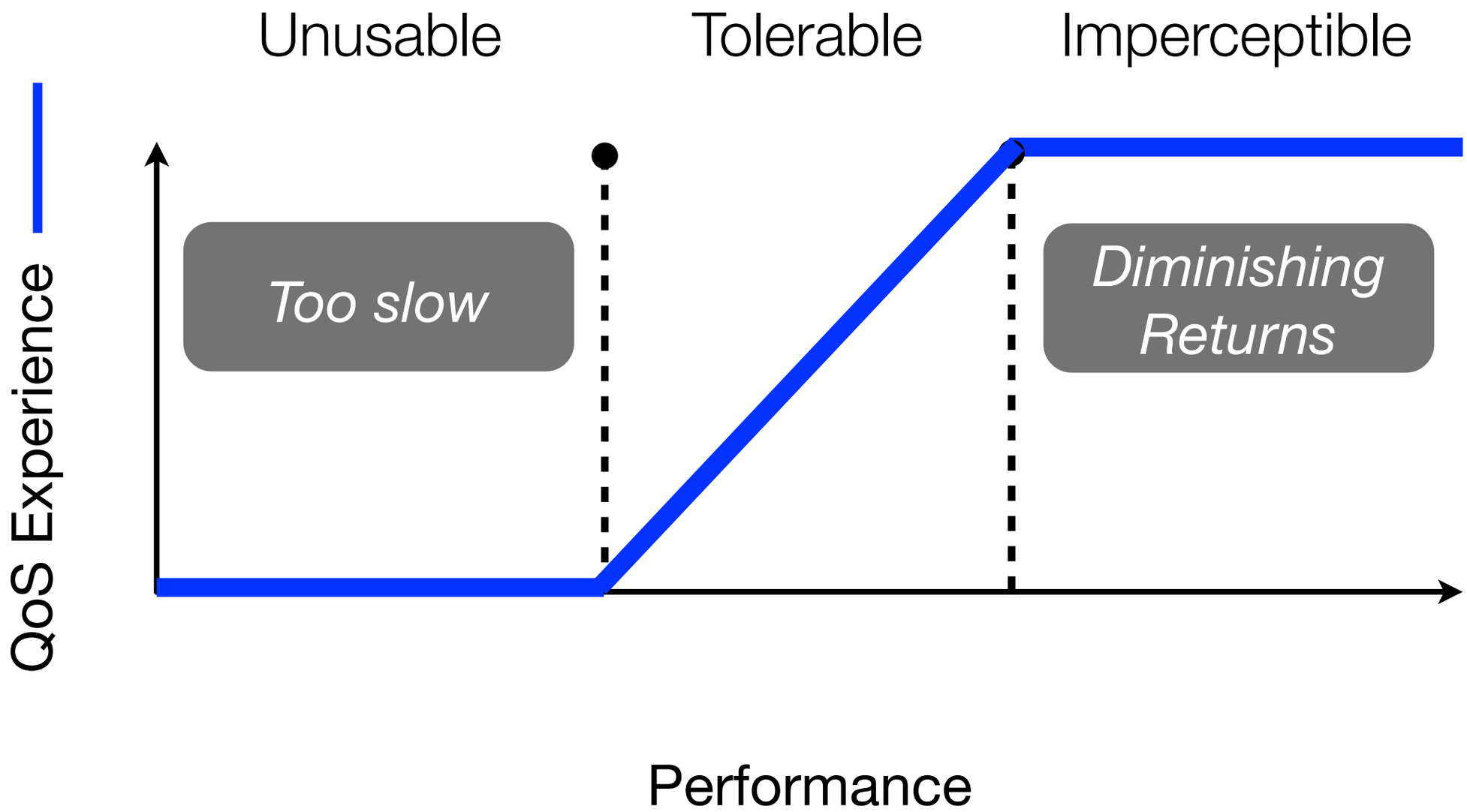

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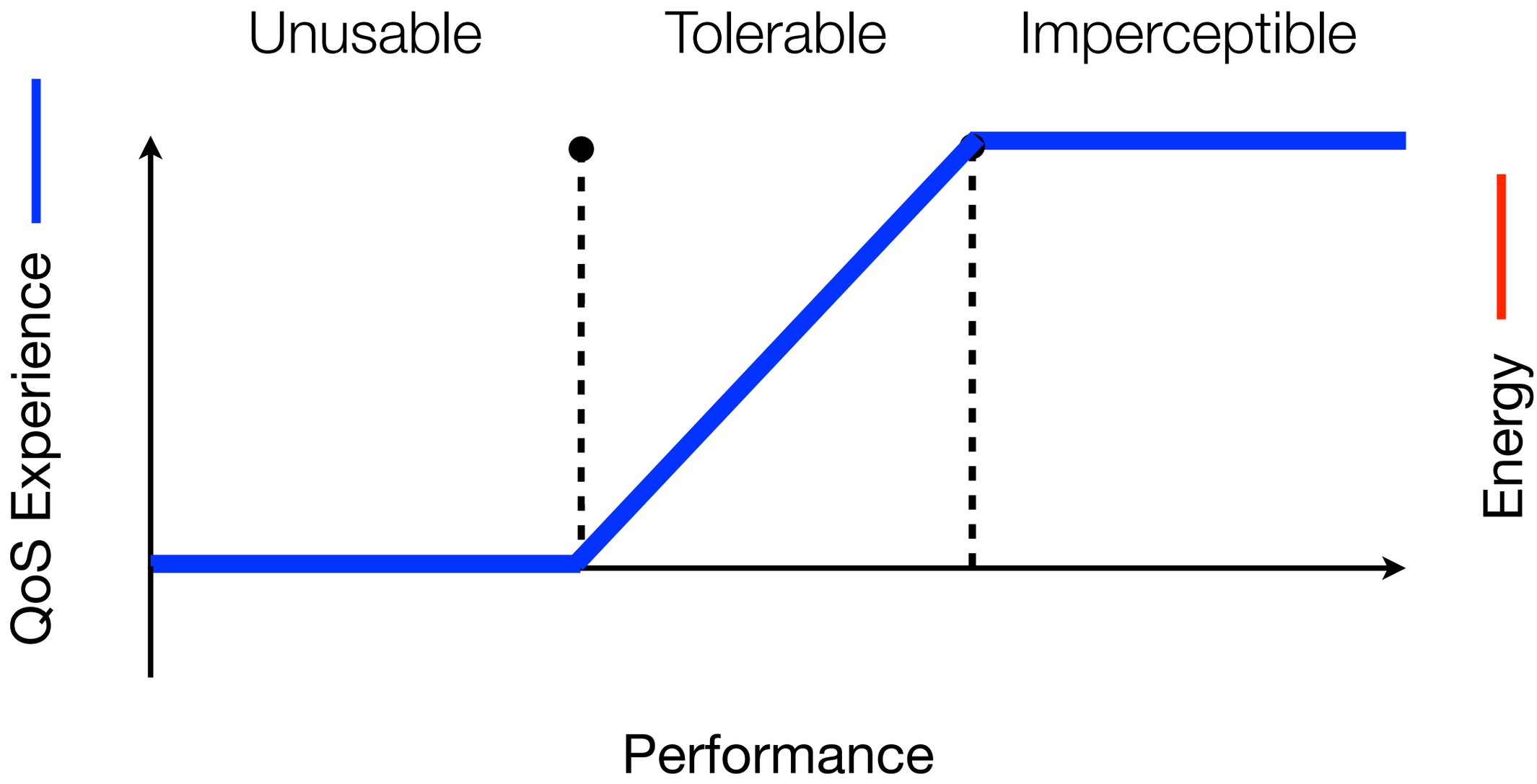

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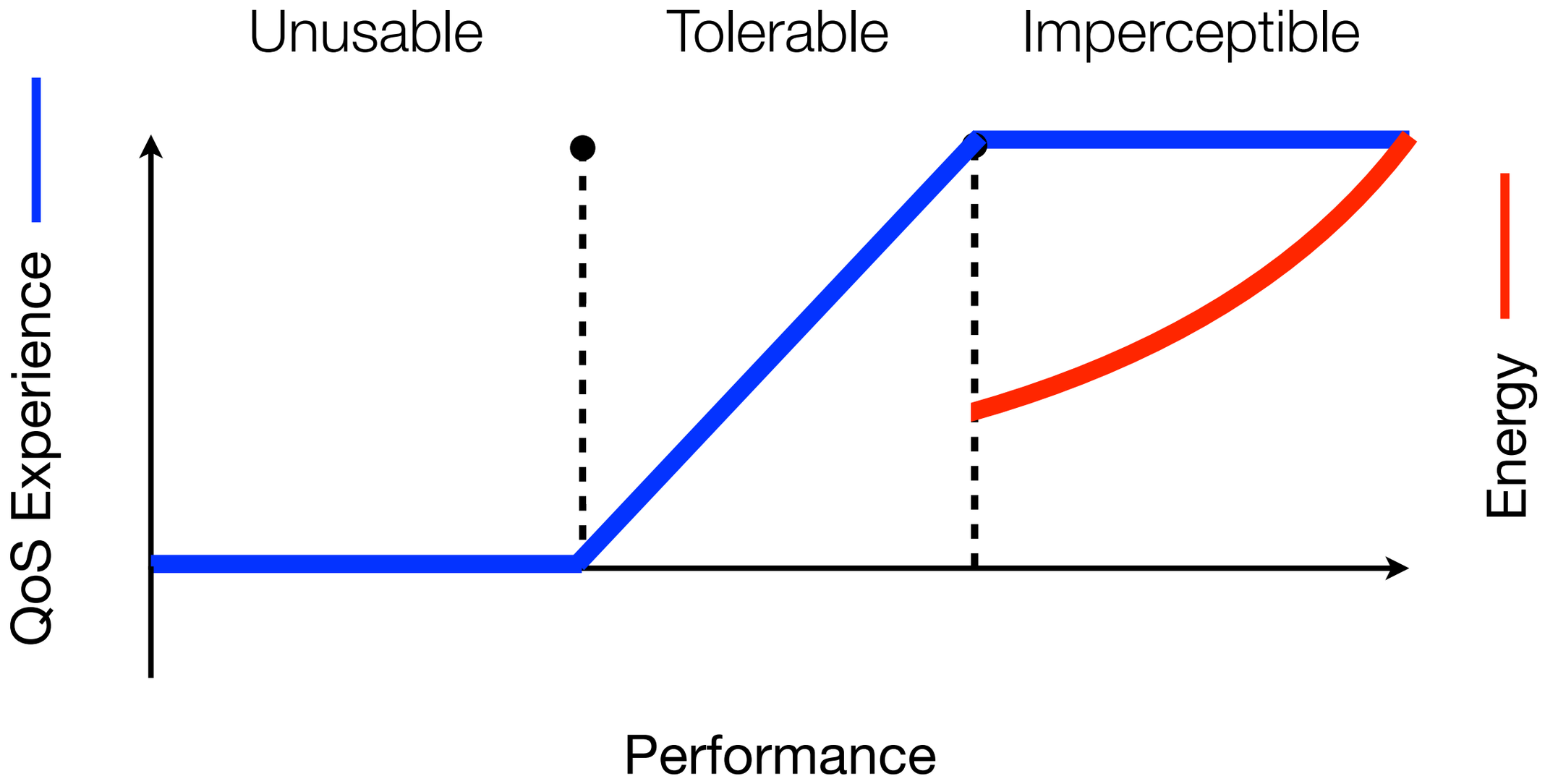

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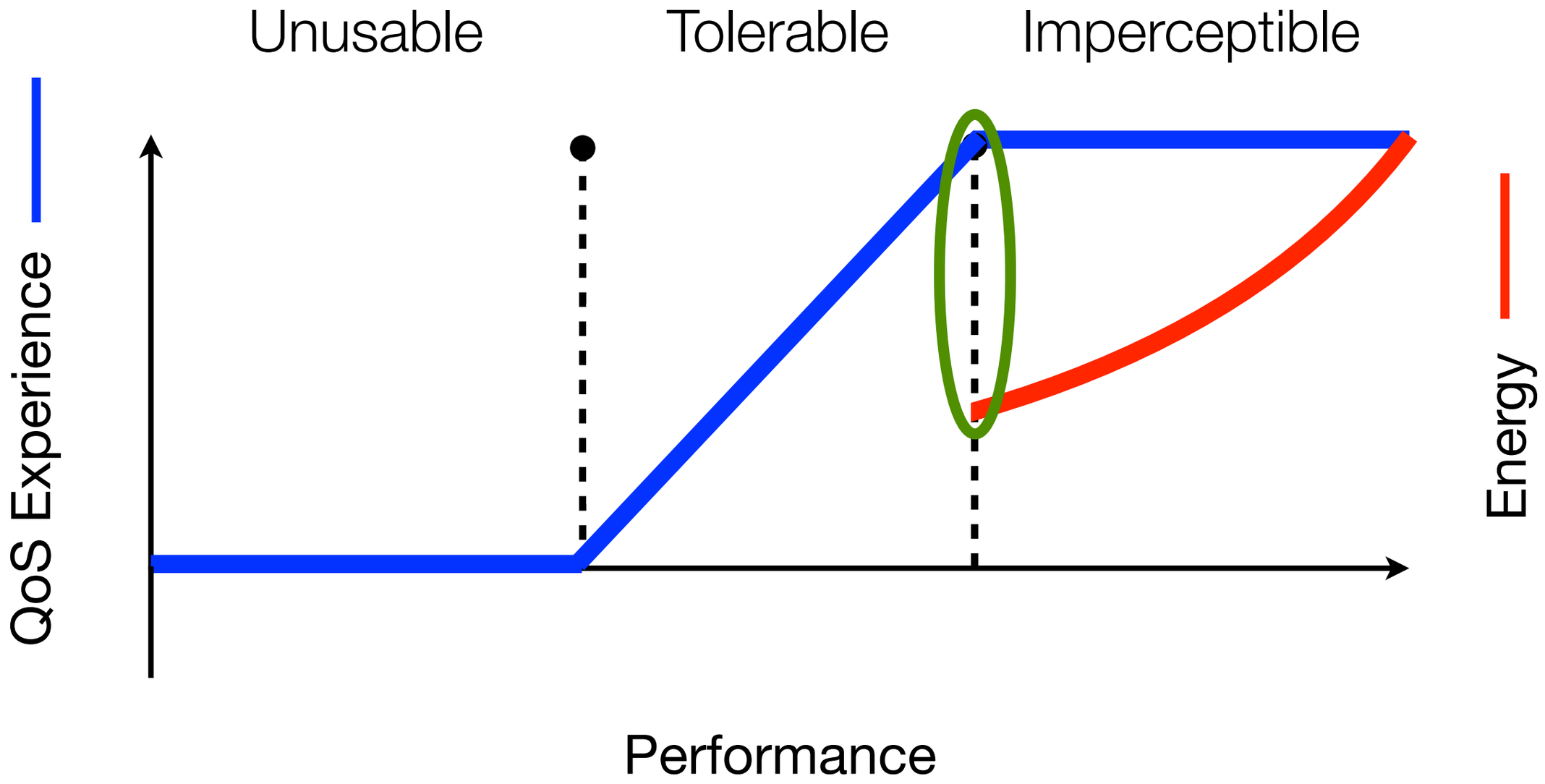

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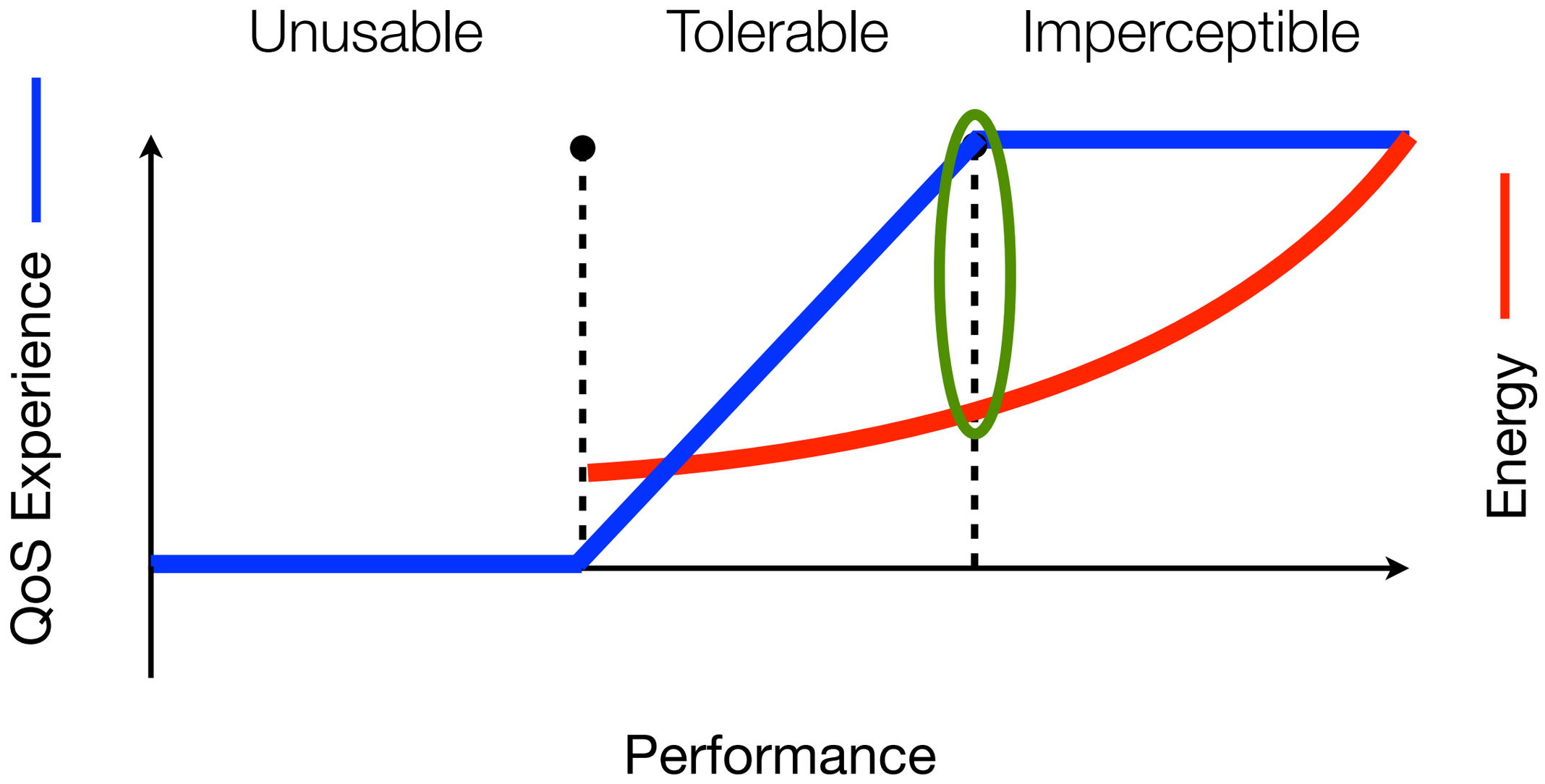

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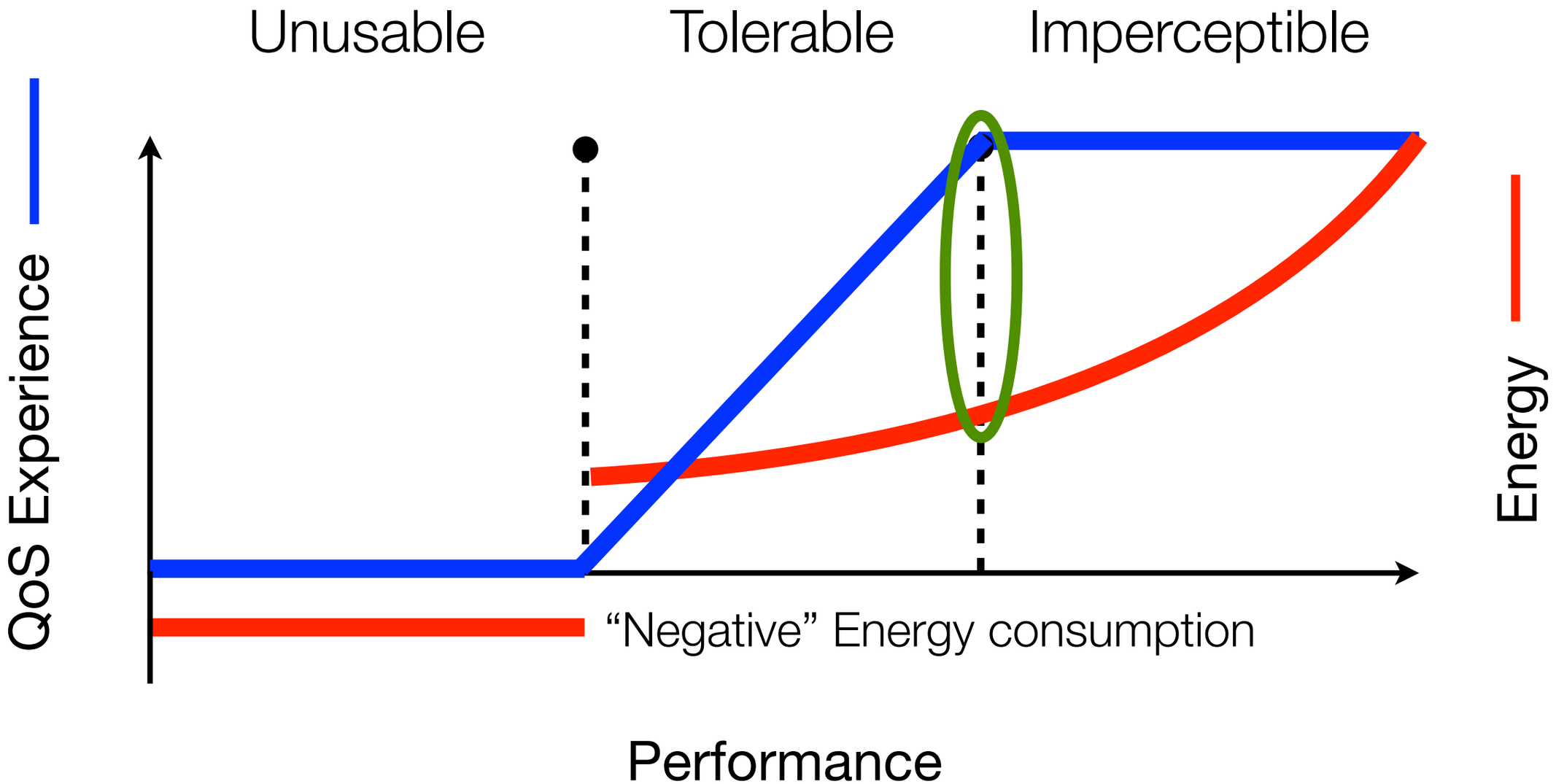

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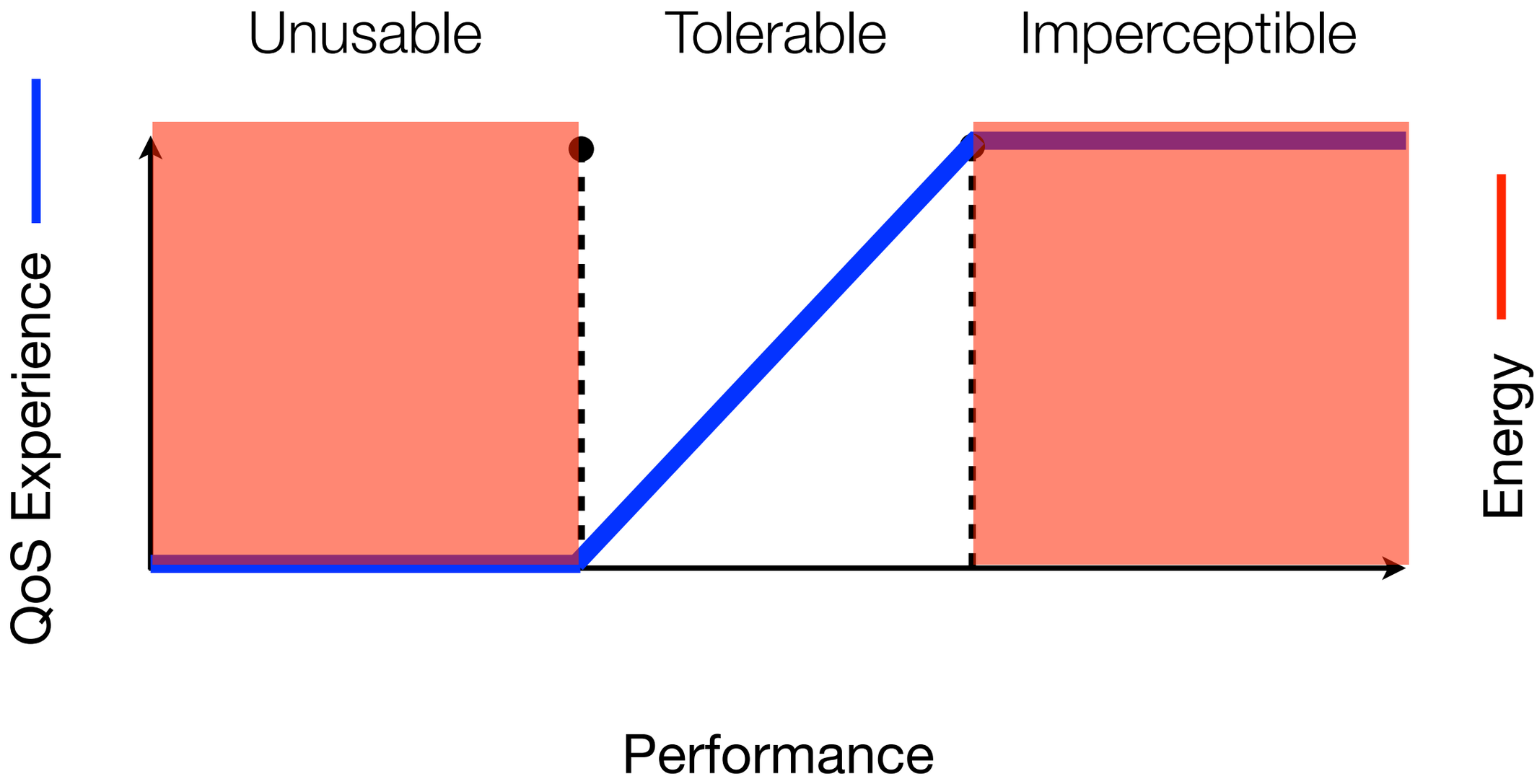

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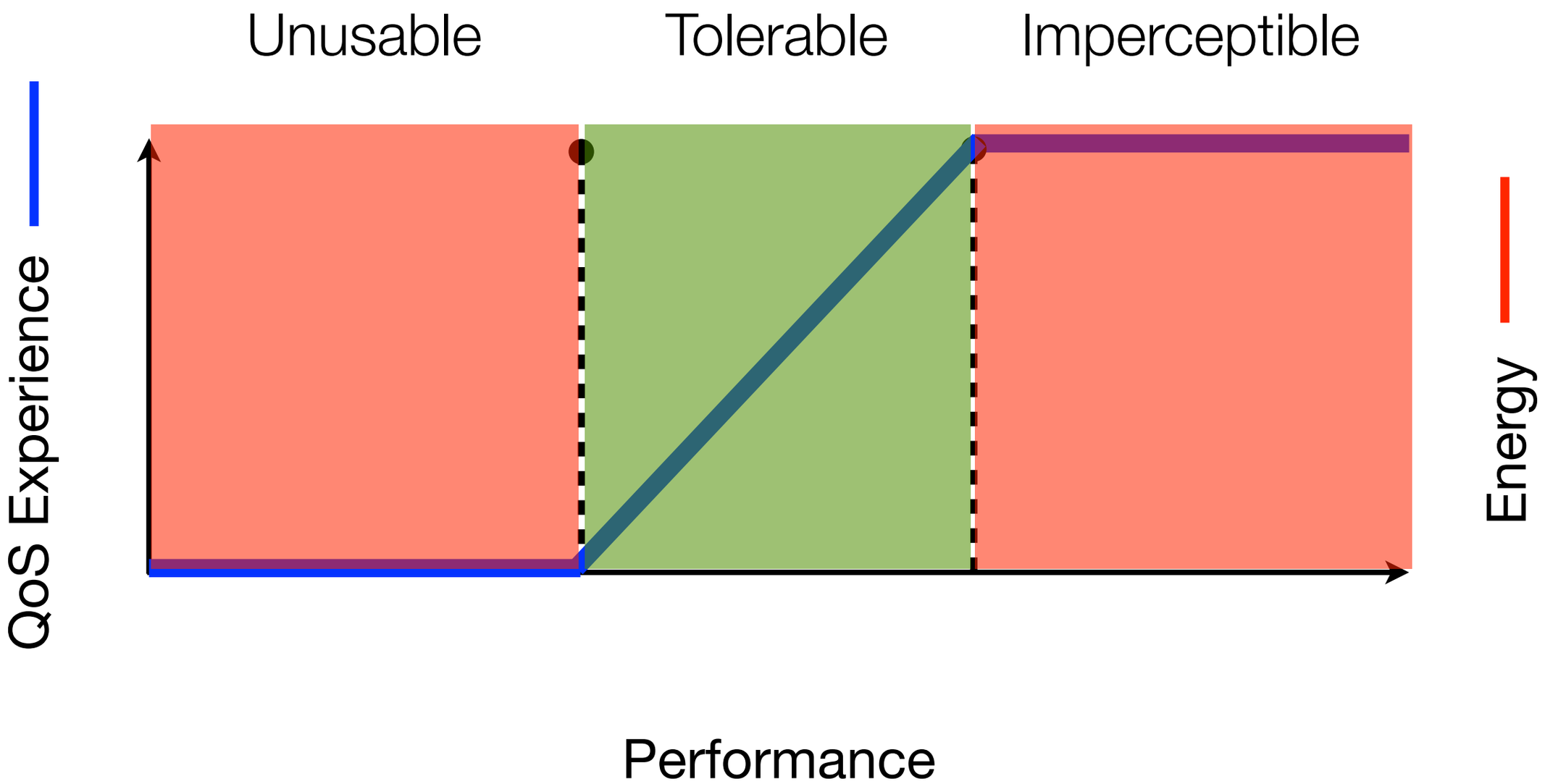

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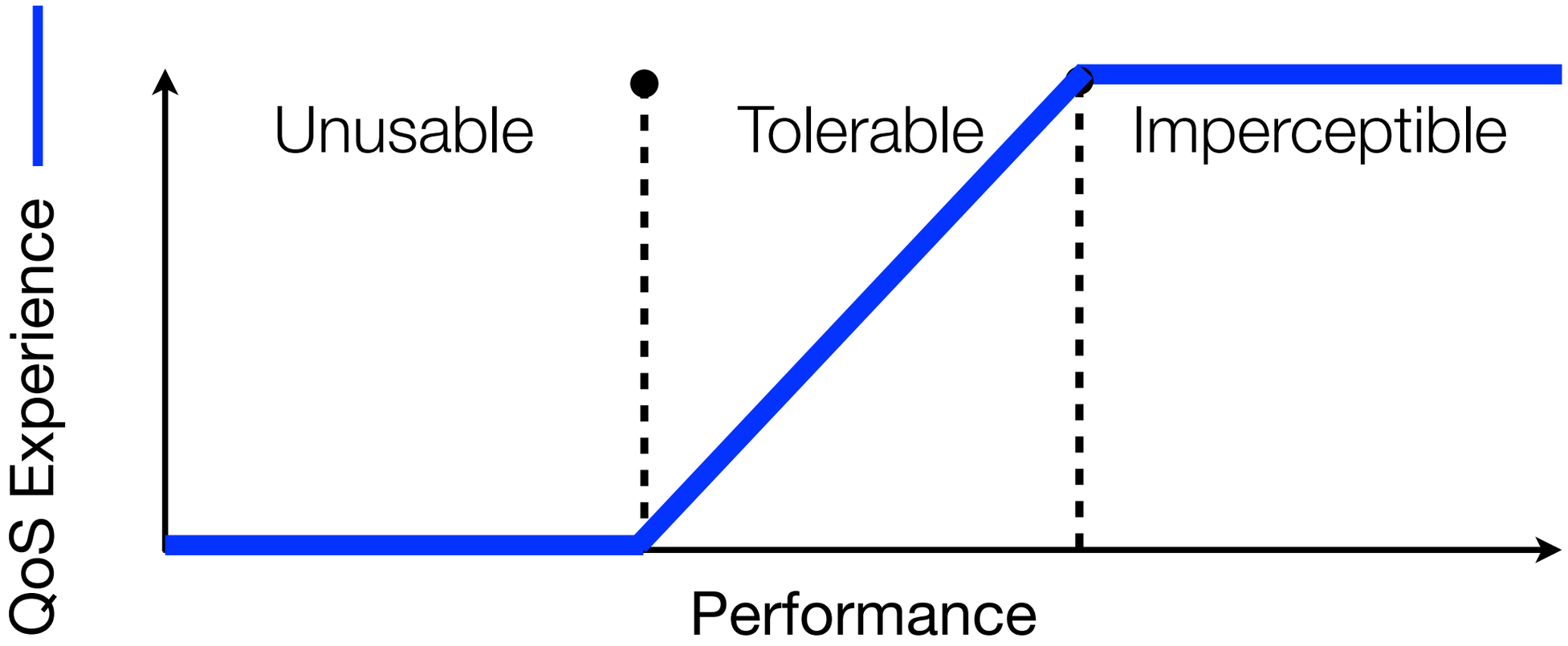
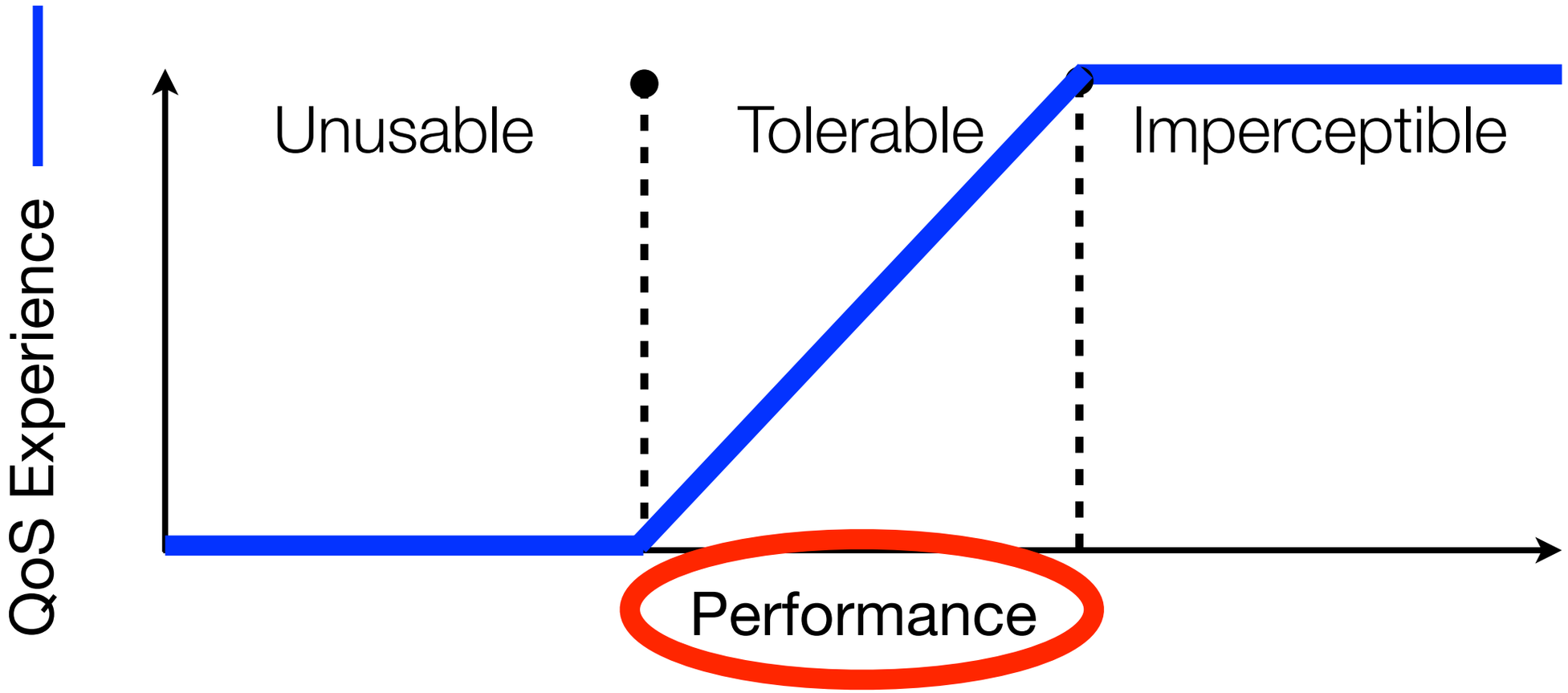
Abstracting Mobile Web QoS



Abstracting Mobile Web QoS

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



Abstracting Mobile Web QoS

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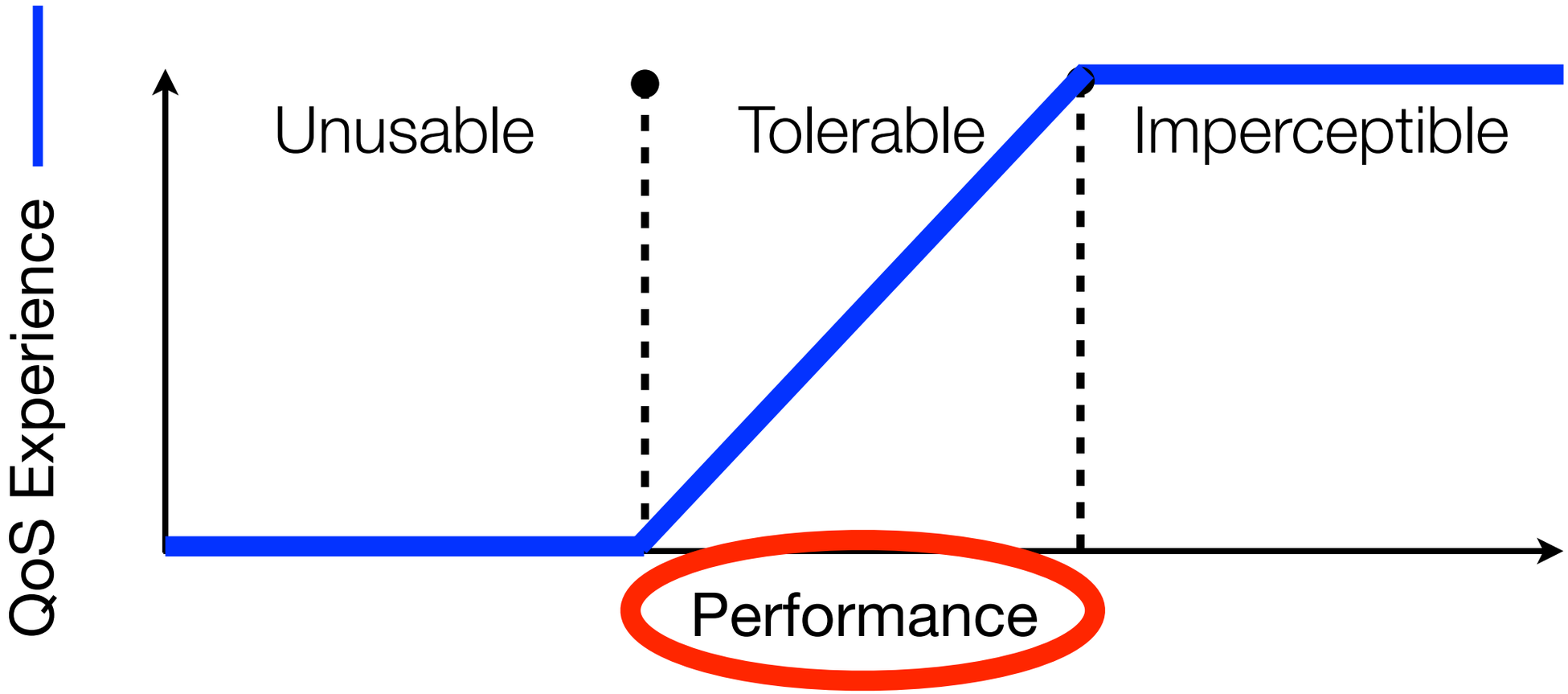
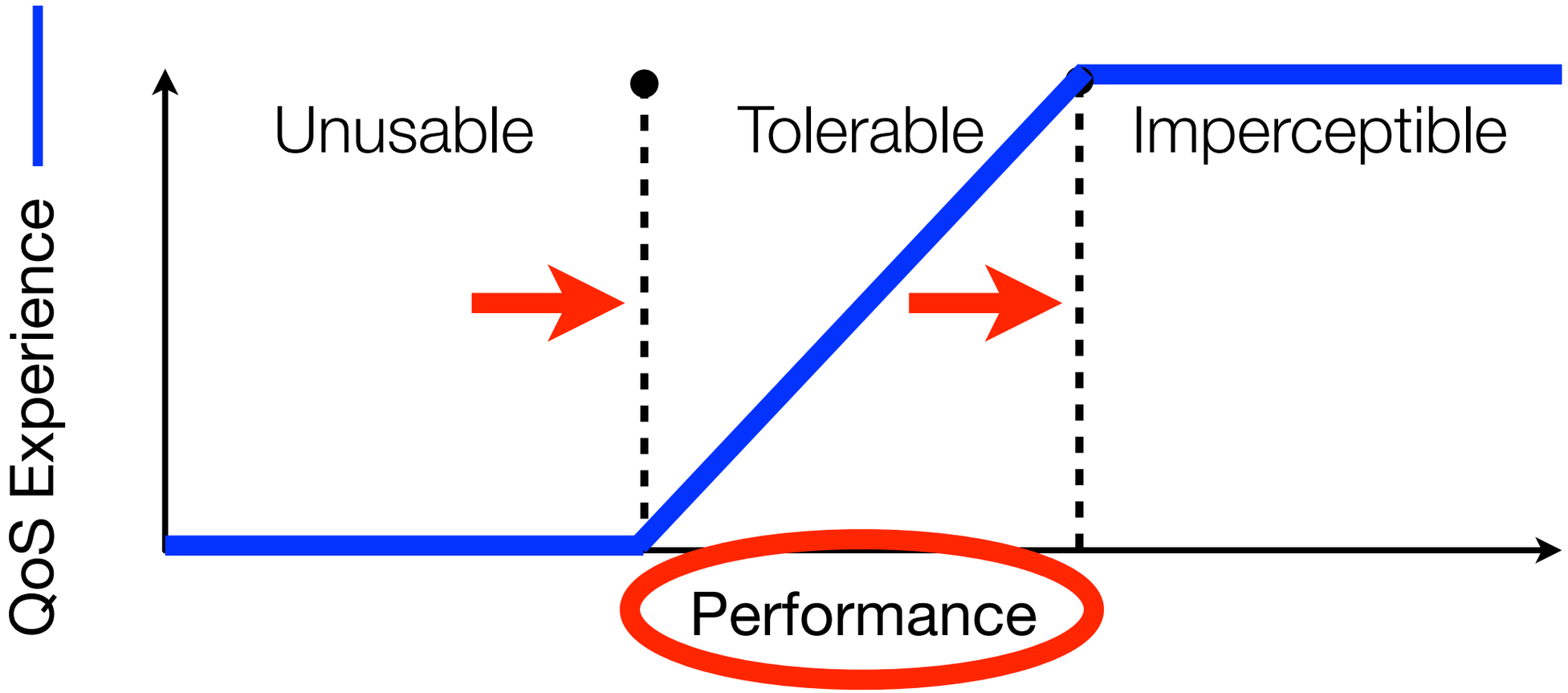
QoS Type



Abstracting Mobile Web QoS

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

QoS Type



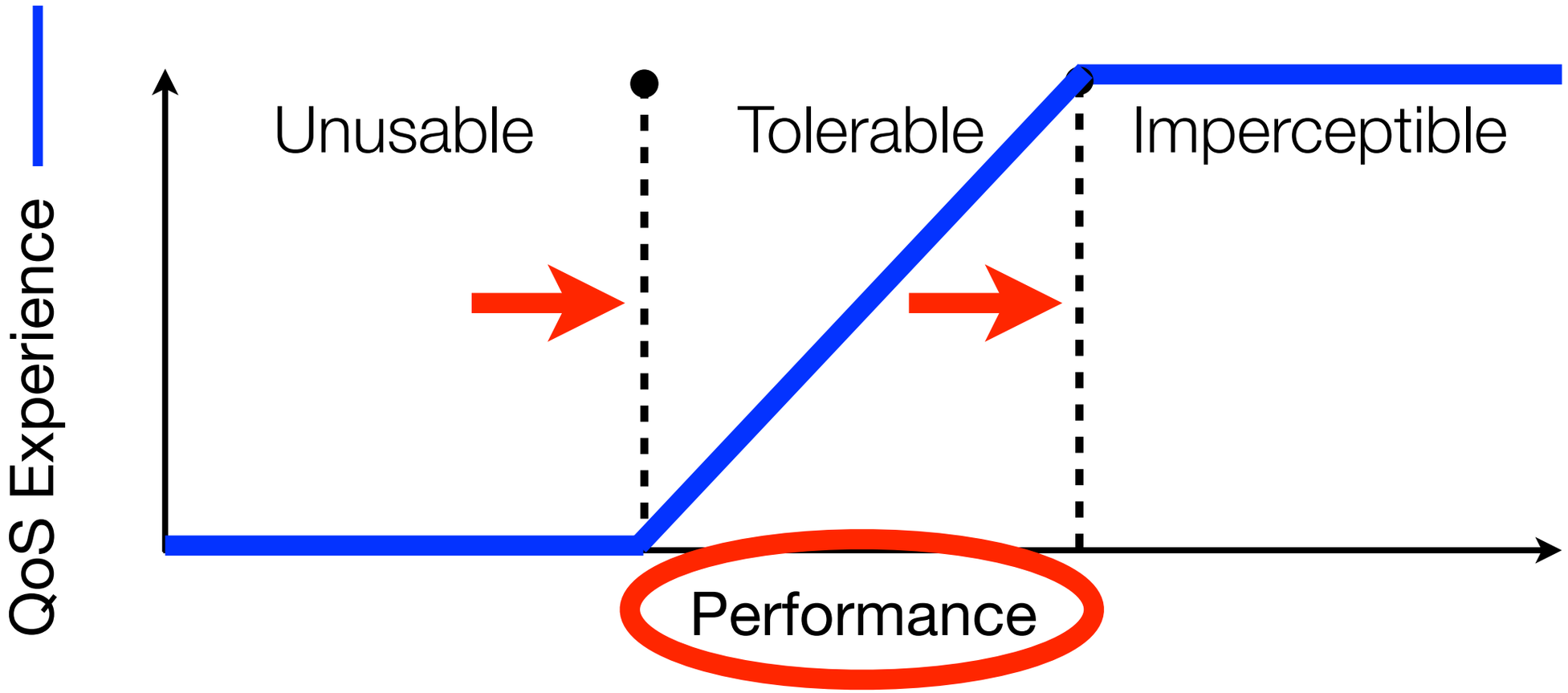
Abstracting Mobile Web QoS

- Performance metric
  - Frame latency vs. Frame throughput

QoS Type

- Threshold performance values
  - Imperceptible target vs. Usable target

QoS Target



Expressing Mobile Web QoS

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

Expressing Mobile Web QoS

element

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Expressing Mobile Web QoS

element **event**

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  <script>
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  </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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Expressing QoS at an event granularity

Expressing Mobile Web QoS

Annotation

```
                element   event

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Expressing Mobile Web QoS

Annotation

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Expressing Mobile Web QoS

Annotation

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

```
<html> <head>
  <style>
    div {
      ontouchend: throughput, low;
    }
  </style>
  <script>
   function animateMove() {
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Expressing Mobile Web QoS


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Expressing Mobile Web QoS


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Annotation

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  <style>
    div {
      ontouchend: throughput, low;
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  </style>
  <script>
    function newAnimateMove() {
      /* New animation code */
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Implementation independent

Expressing Mobile Web QoS


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Implementation independent

Expressing Mobile Web QoS

CSS
Cascading Style Sheet

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

Annotation

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<html> <head>
  <style>
    div {
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  </style>
  <script>
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  <div ontouchend="animateMove()">
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```

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

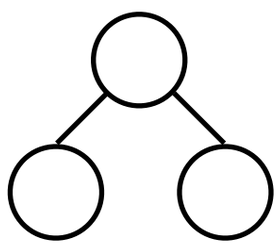
GreenWeb Annotation Process

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

GreenWeb Annotation Process

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

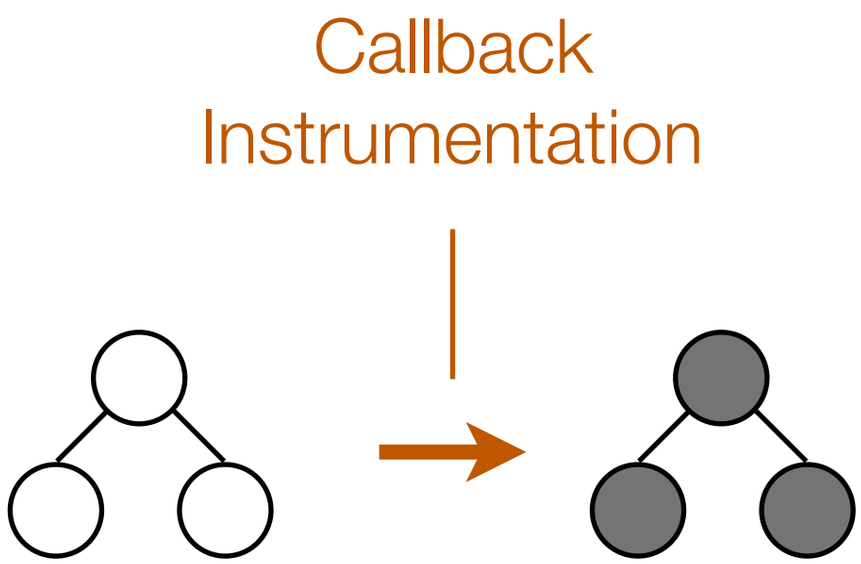
GreenWeb Annotation Process



GreenWeb-annotated application

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

GreenWeb Annotation Process



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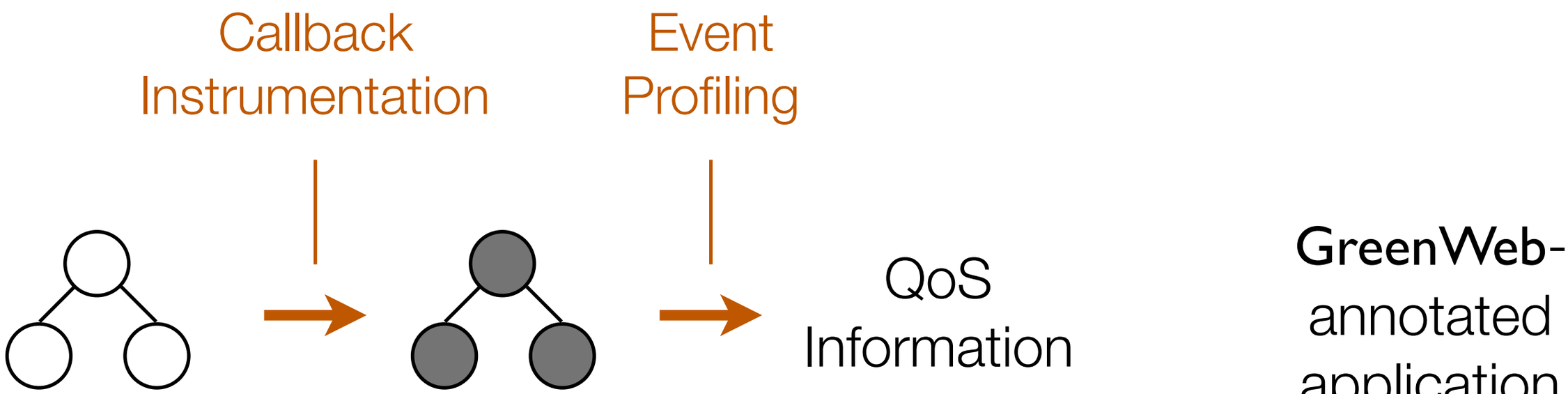
GreenWeb Annotation Process



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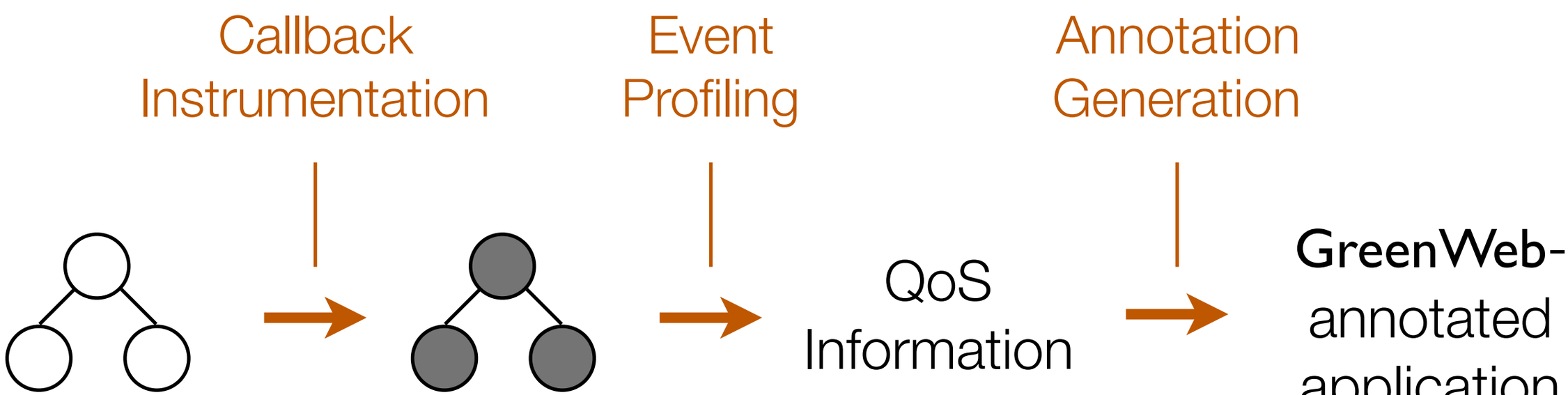
GreenWeb Annotation Process



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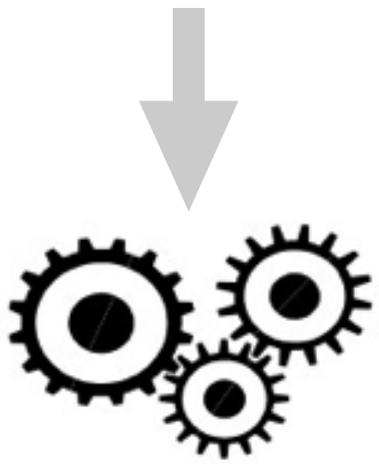
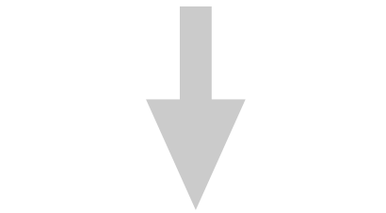
GreenWeb: Language for Energy-Efficiency





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

GreenWeb 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

QoS Annotations

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QoS type: latency

QoS target: 16 ms

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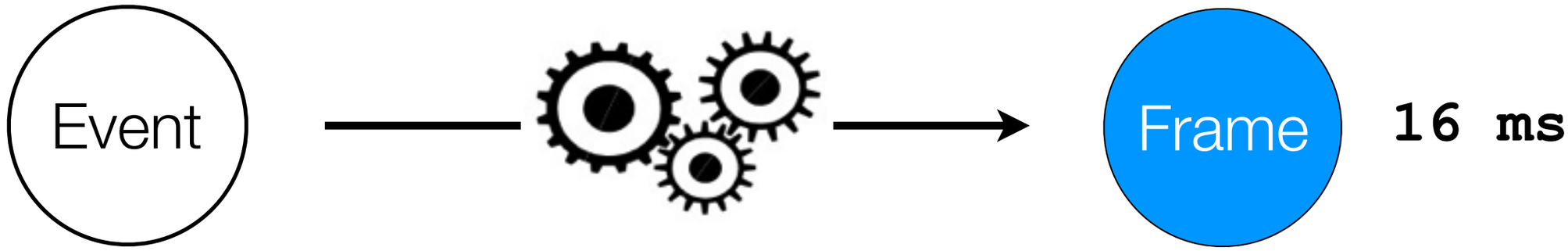

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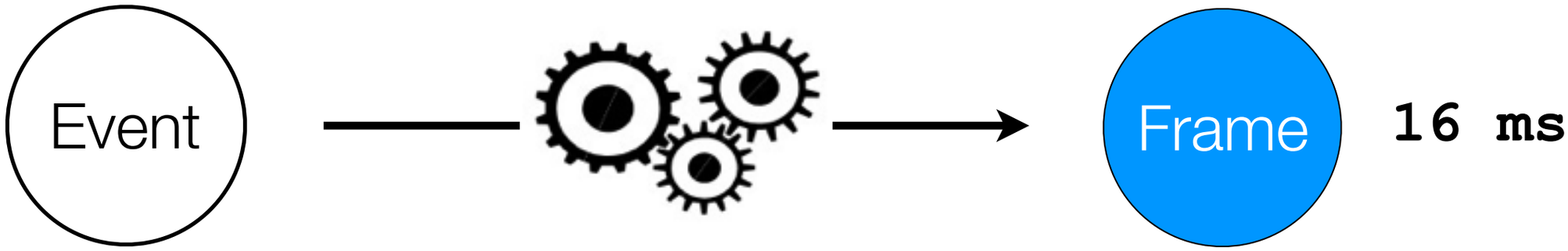

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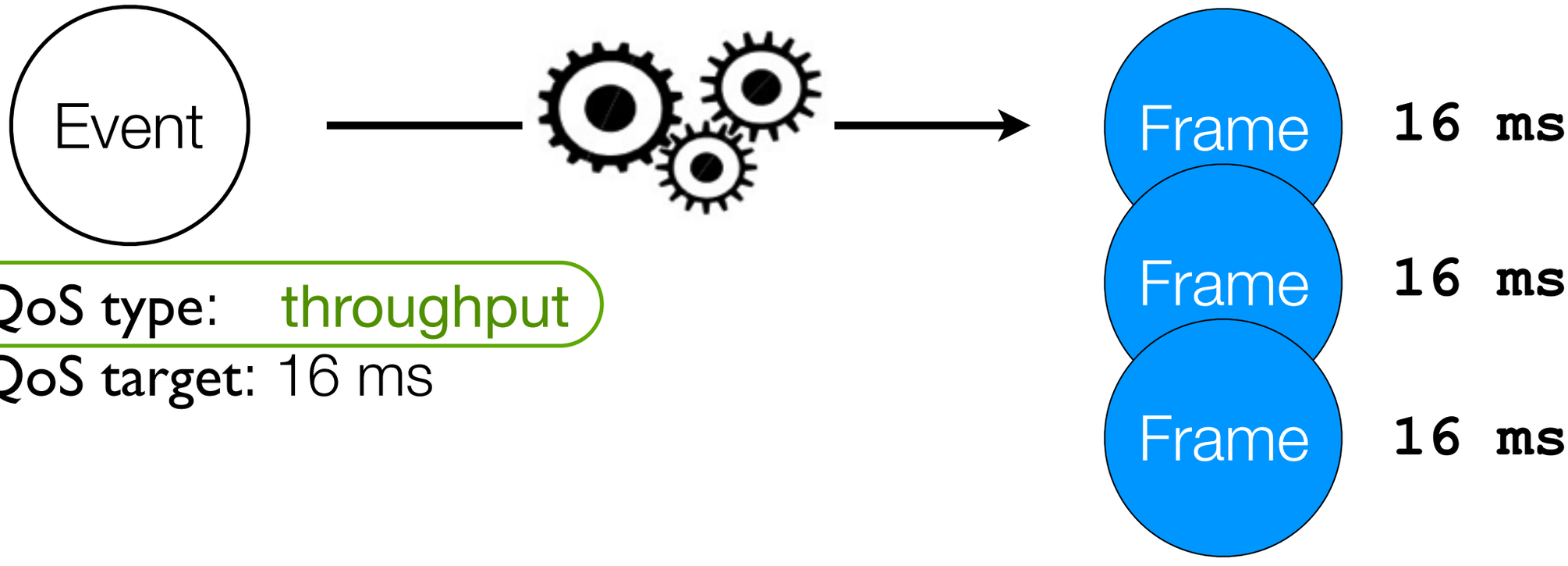

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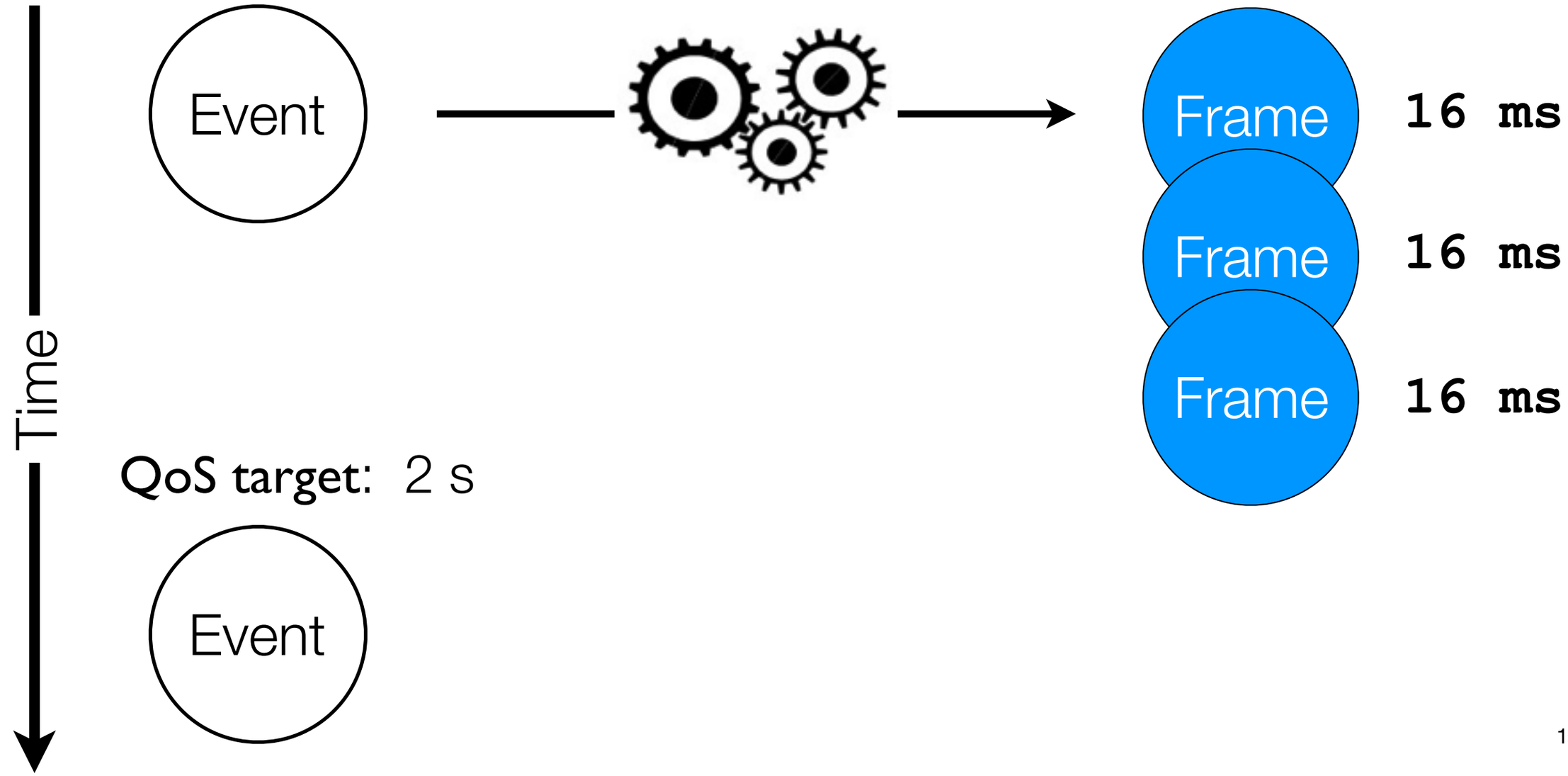

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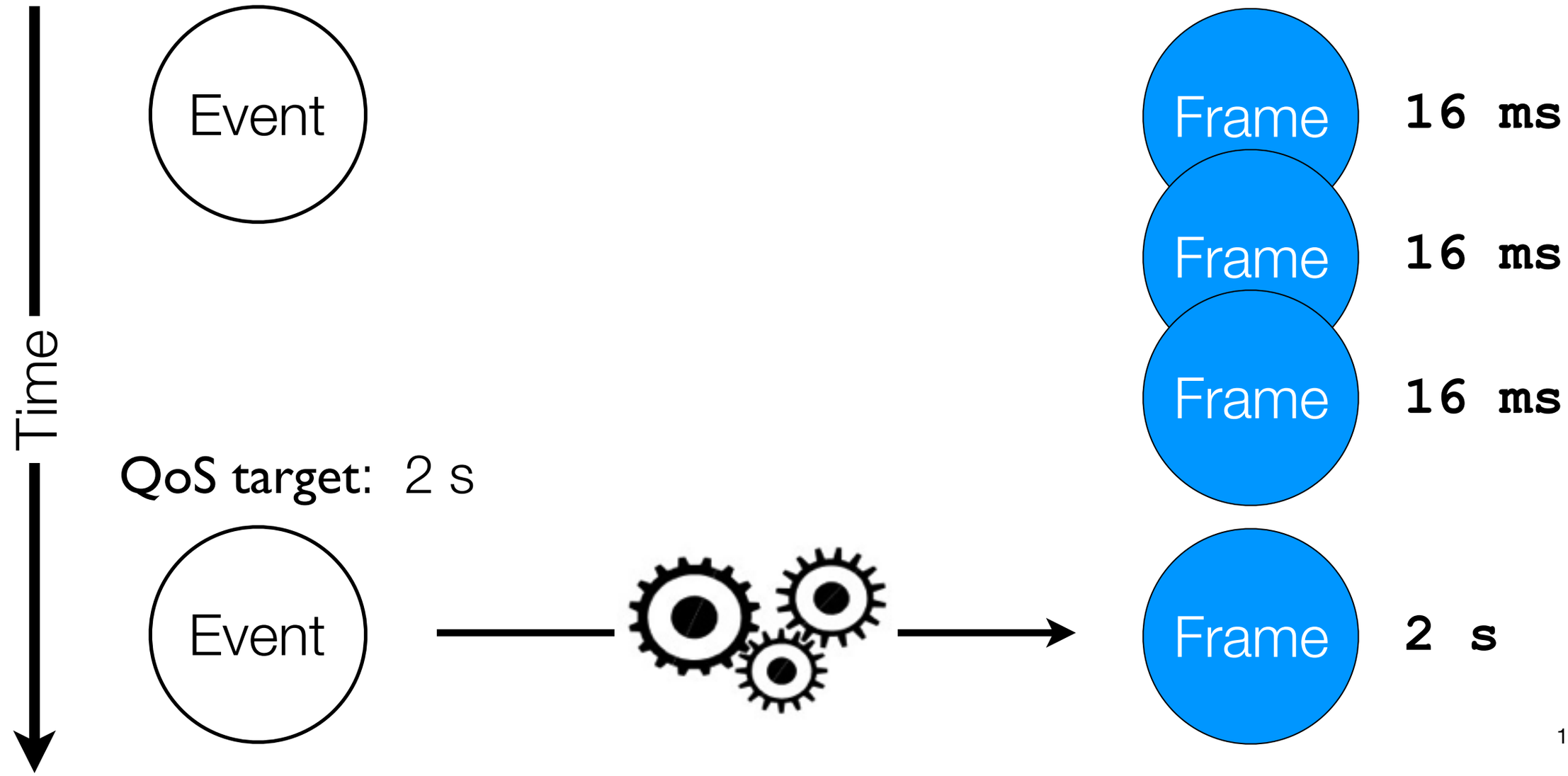

GreenWeb Runtime Overview

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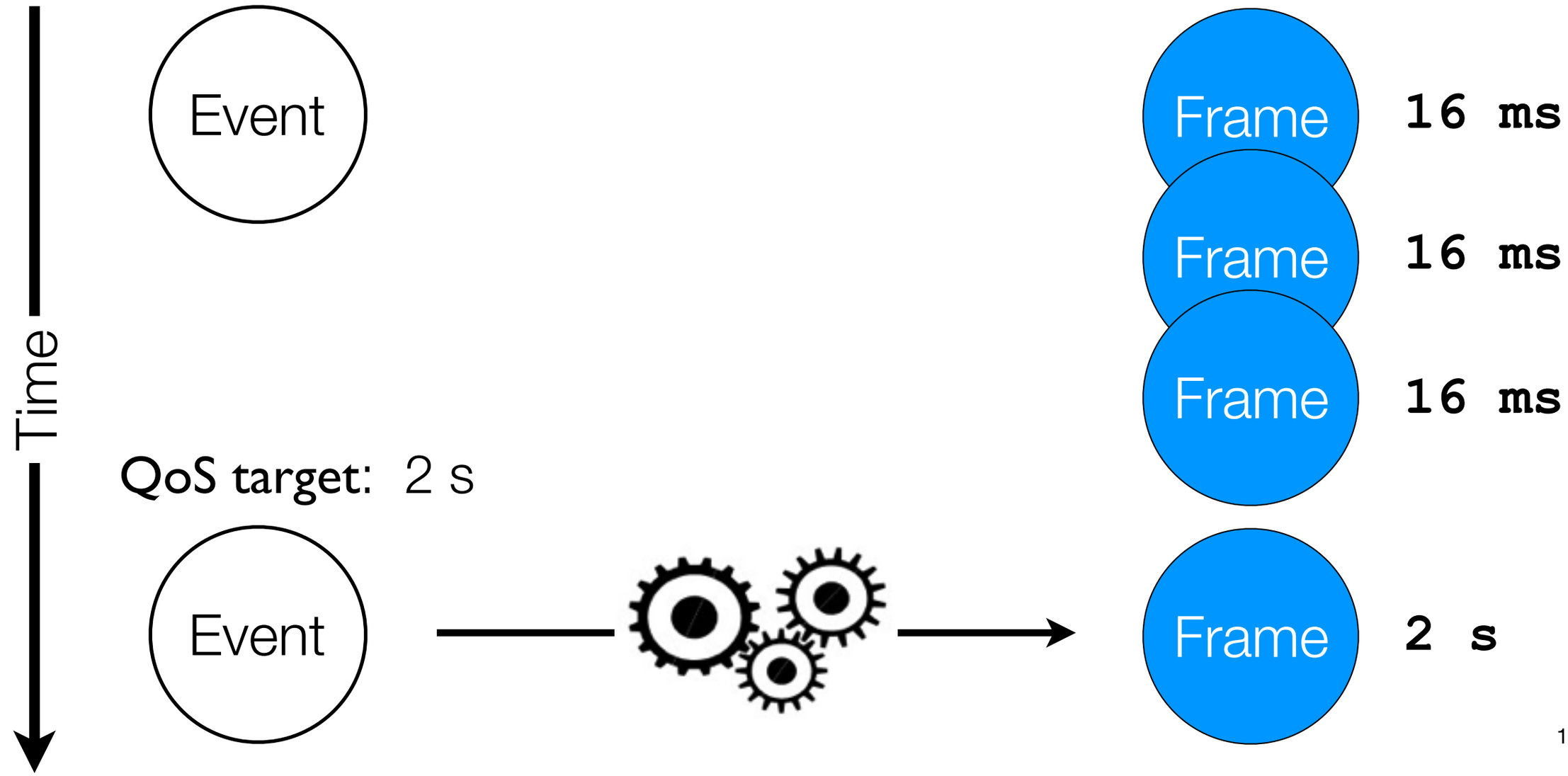


GreenWeb Runtime Overview

Runtime Objective

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

{

1. Frame Association

Time

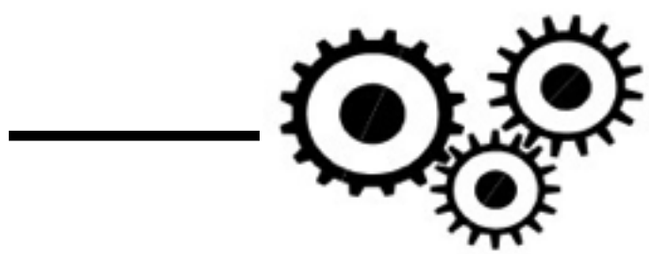
Event

Frame — 16 ms

Frame — 16 ms

Frame — 16 ms

Event



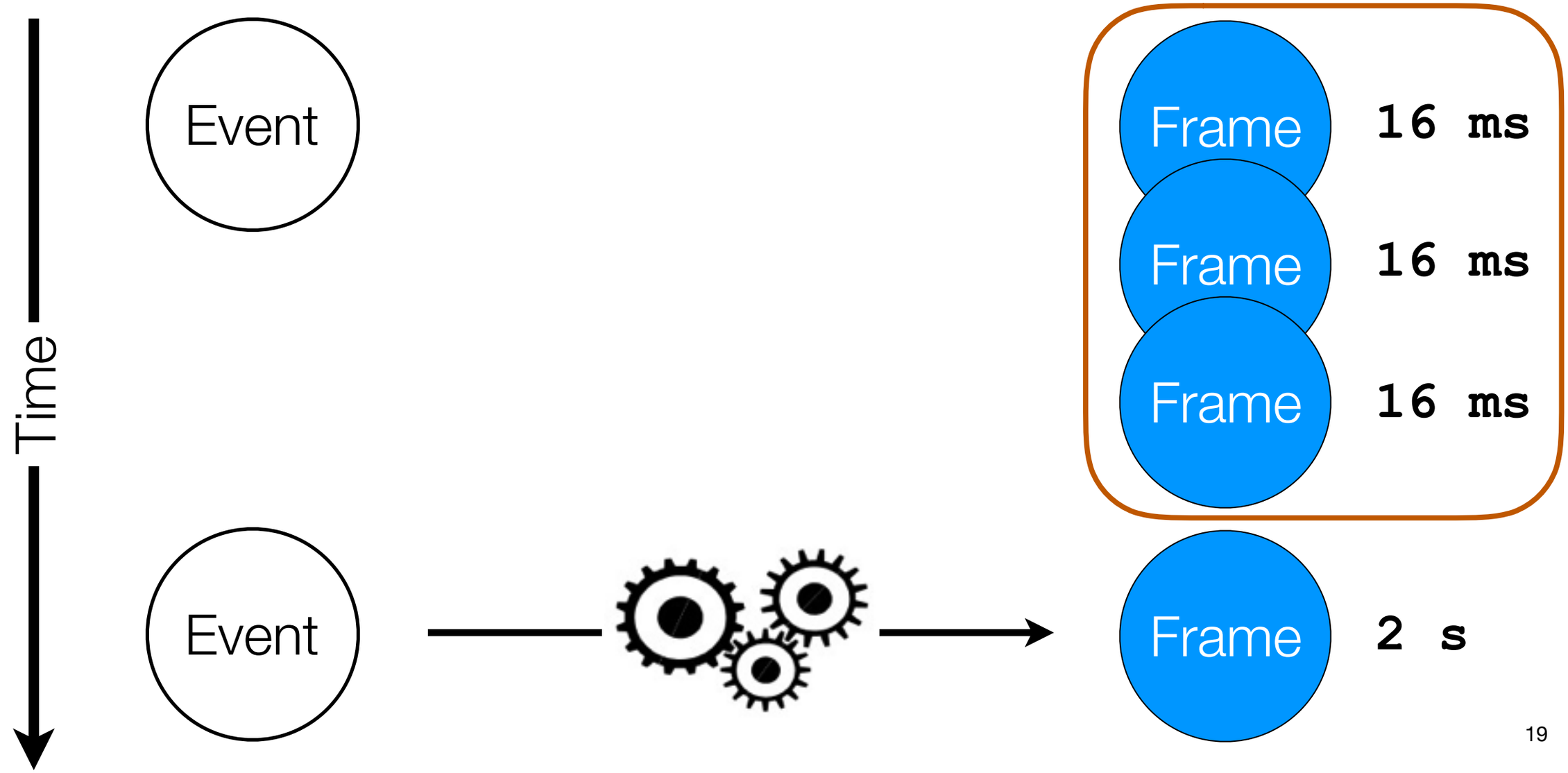
Frame — 2 s

GreenWeb Runtime Overview

Runtime Objective

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

1. Frame Association
2. Frame Scheduling



Frame Association

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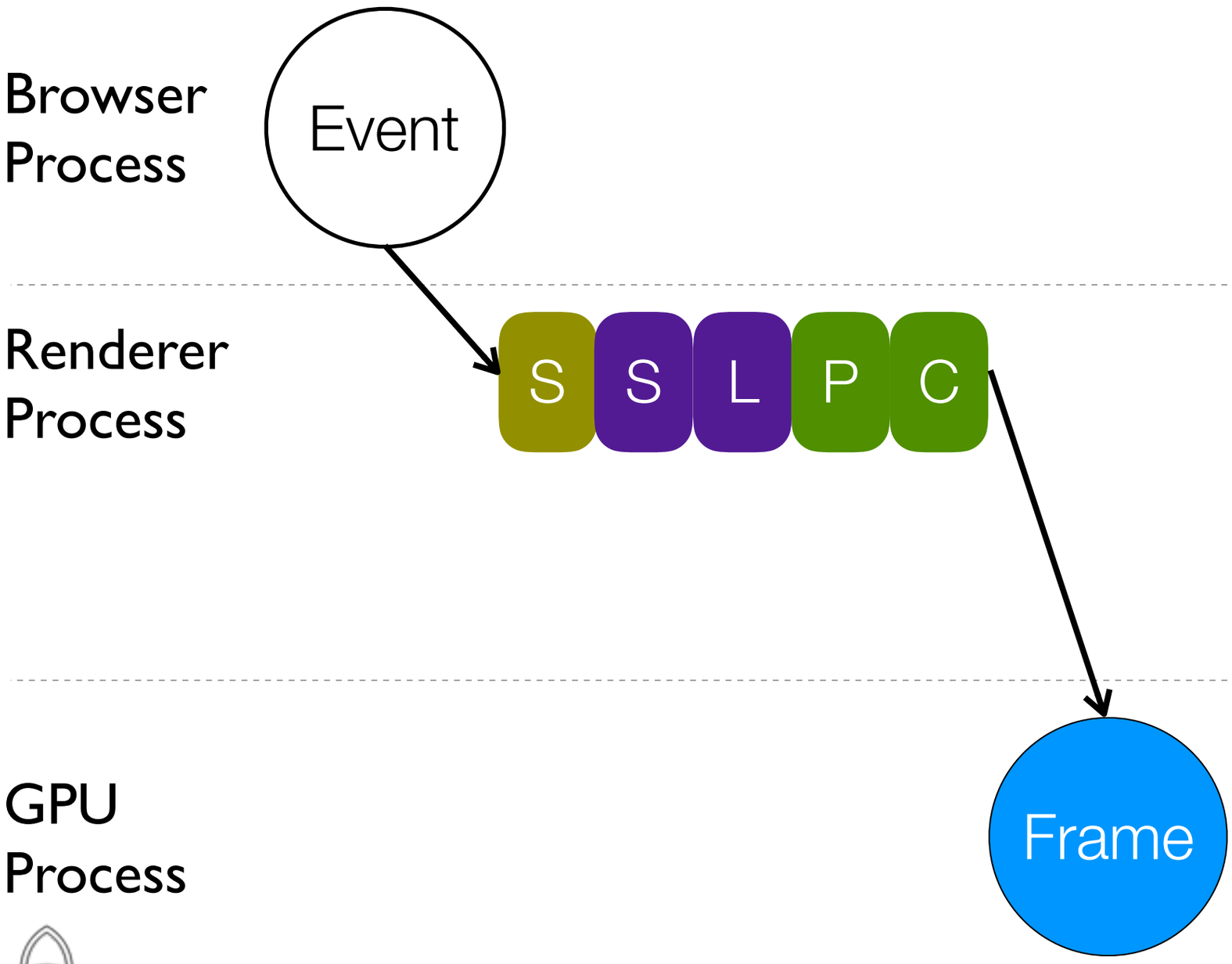

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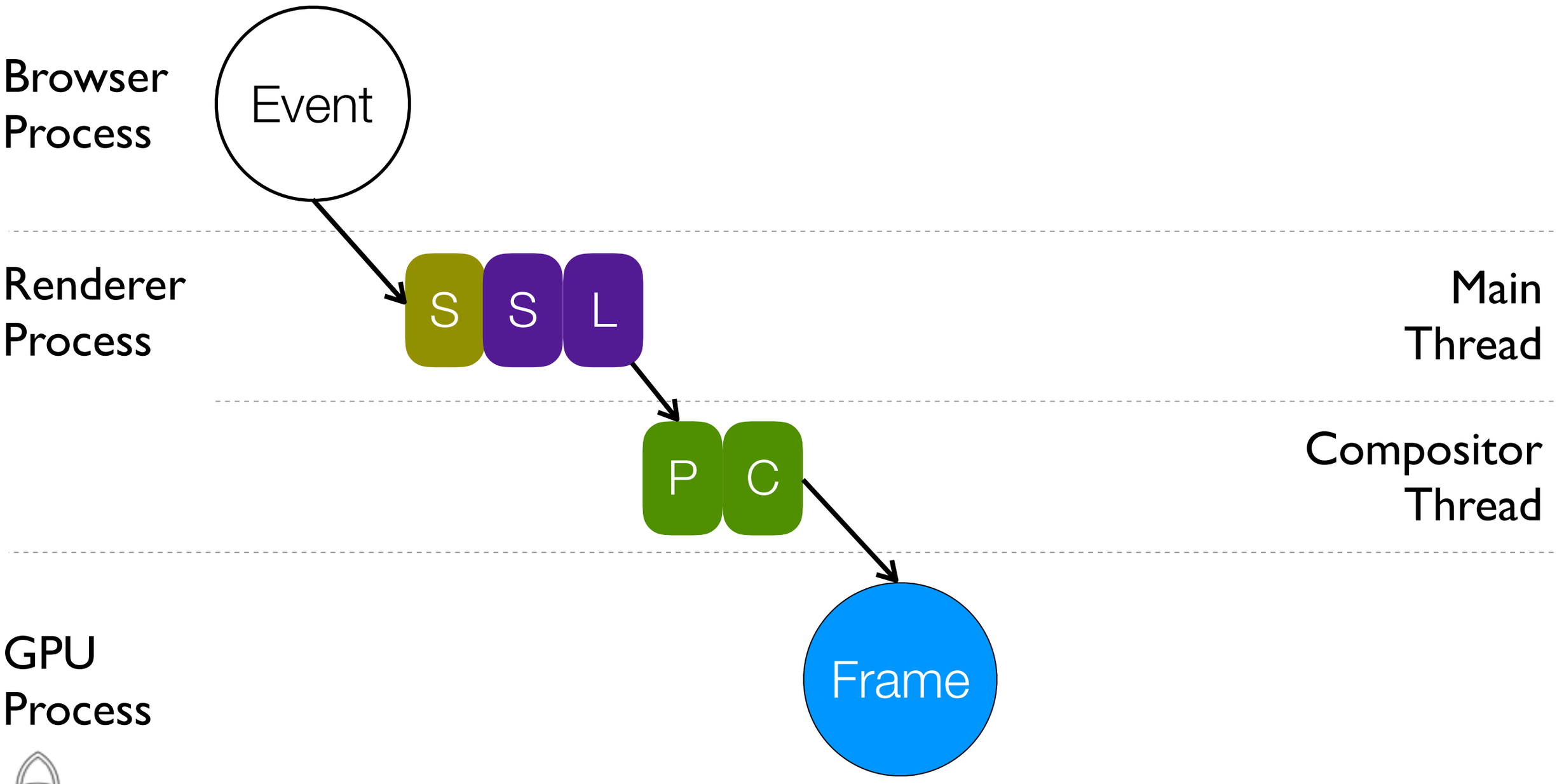

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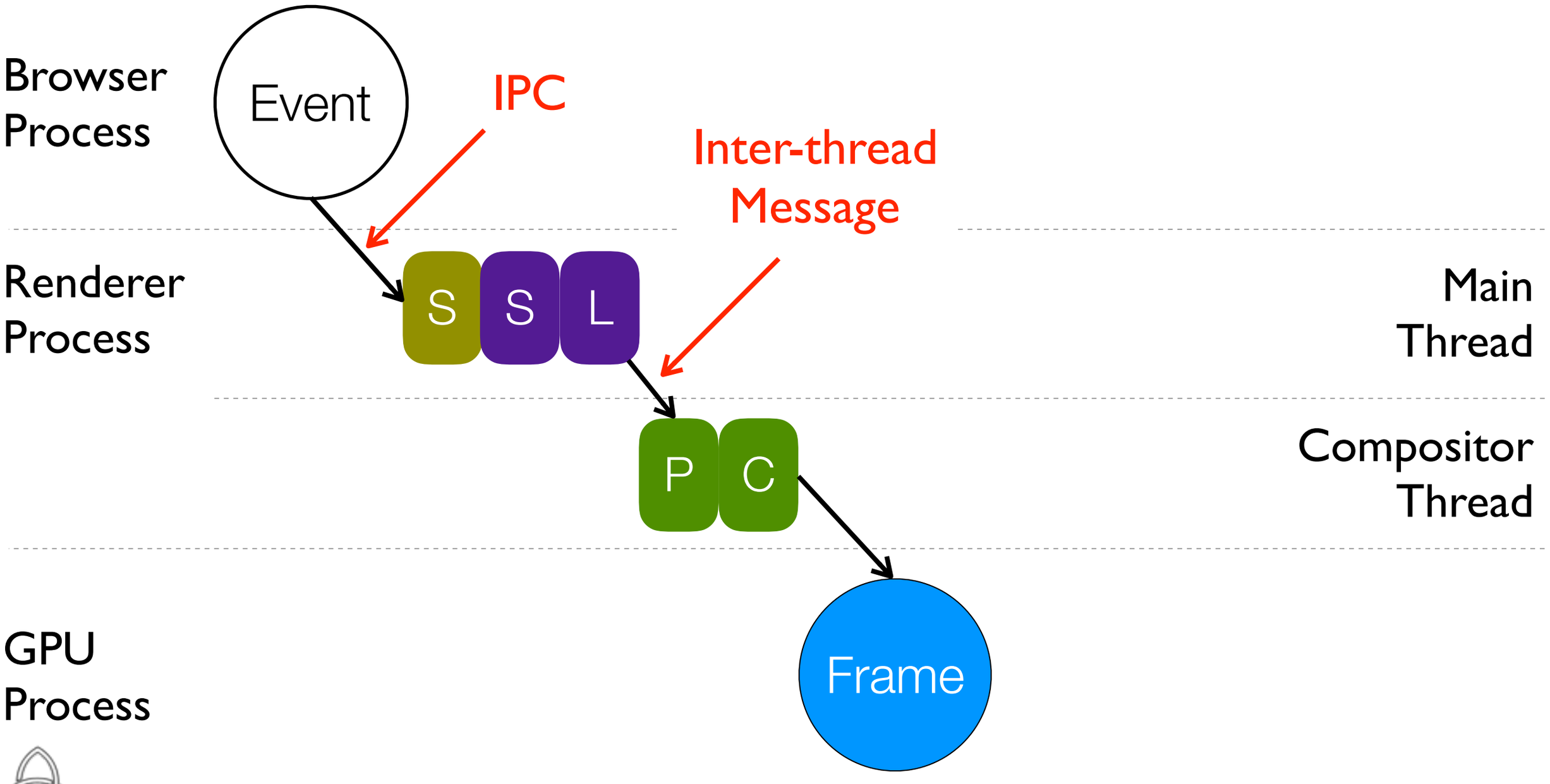

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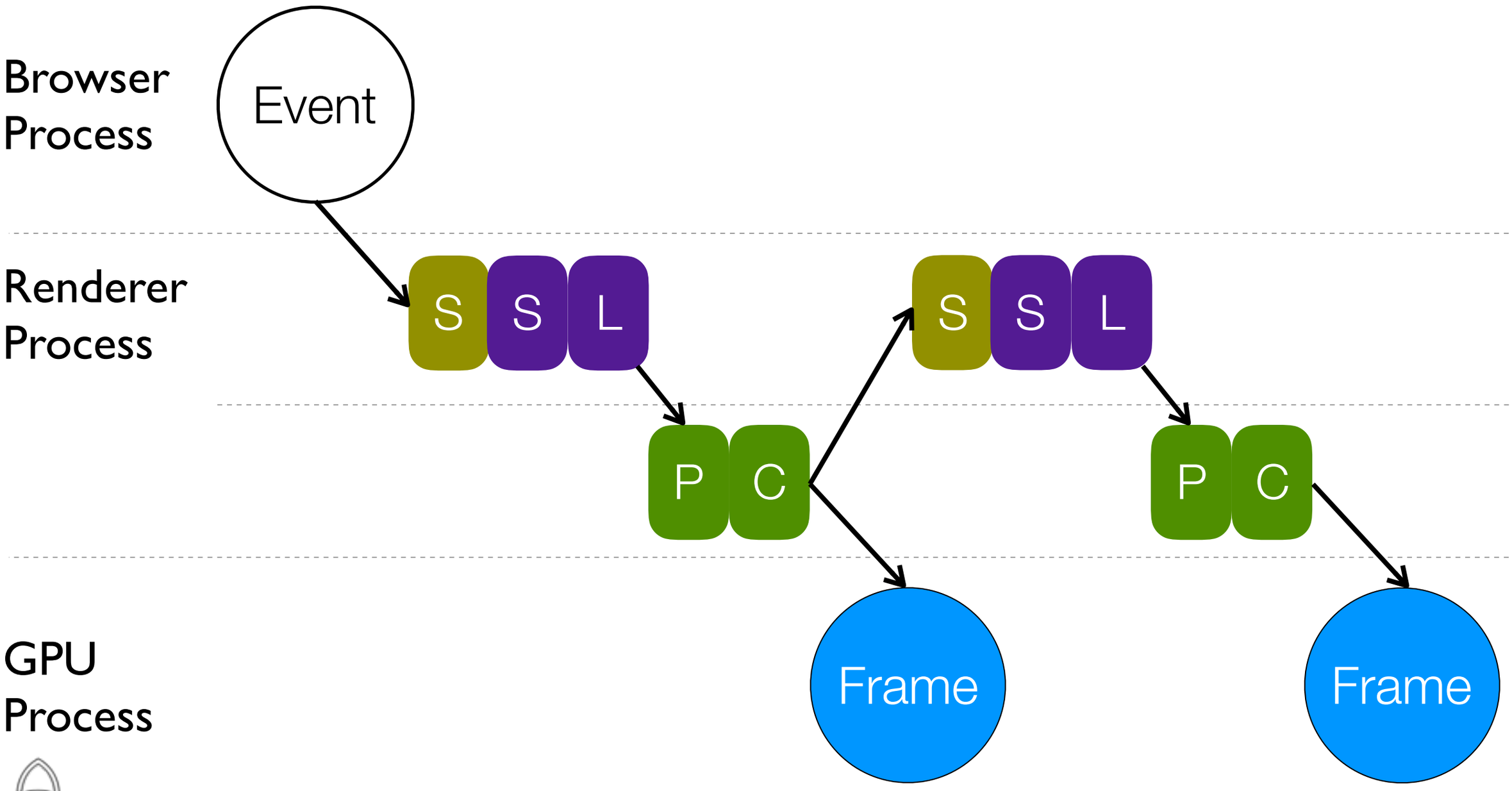
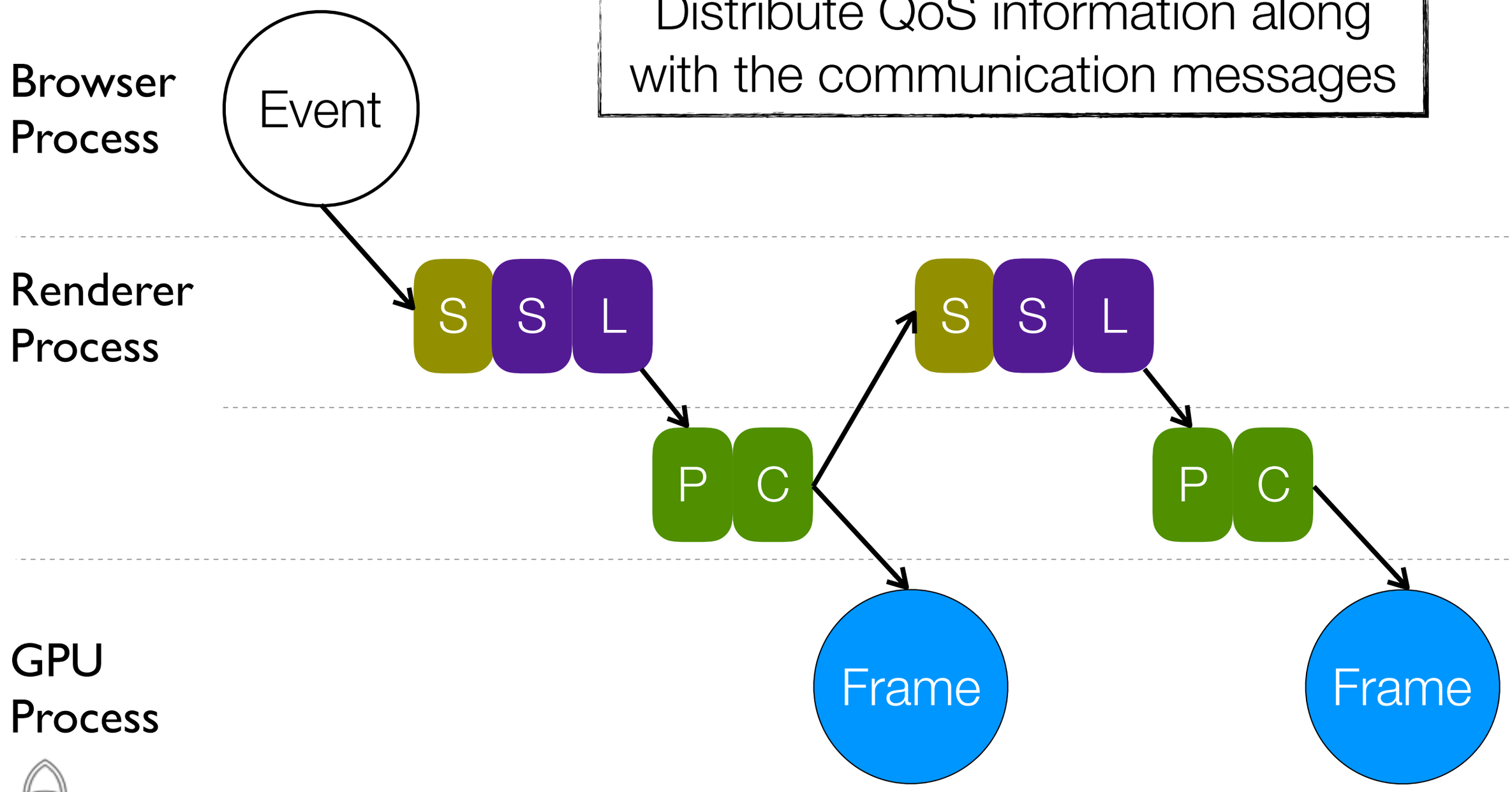


Frame Association

Distribute QoS information along with the communication messages



Choices of Energy-saving Techniques

GreenWeb can support a range of energy saving techniques

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- Dynamic resolution scaling [MobiCom 2015]
- Power-saving display colors [MobiSys 2012]
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- ACMP-based hardware mechanism

ACMP-based Hardware Substrate

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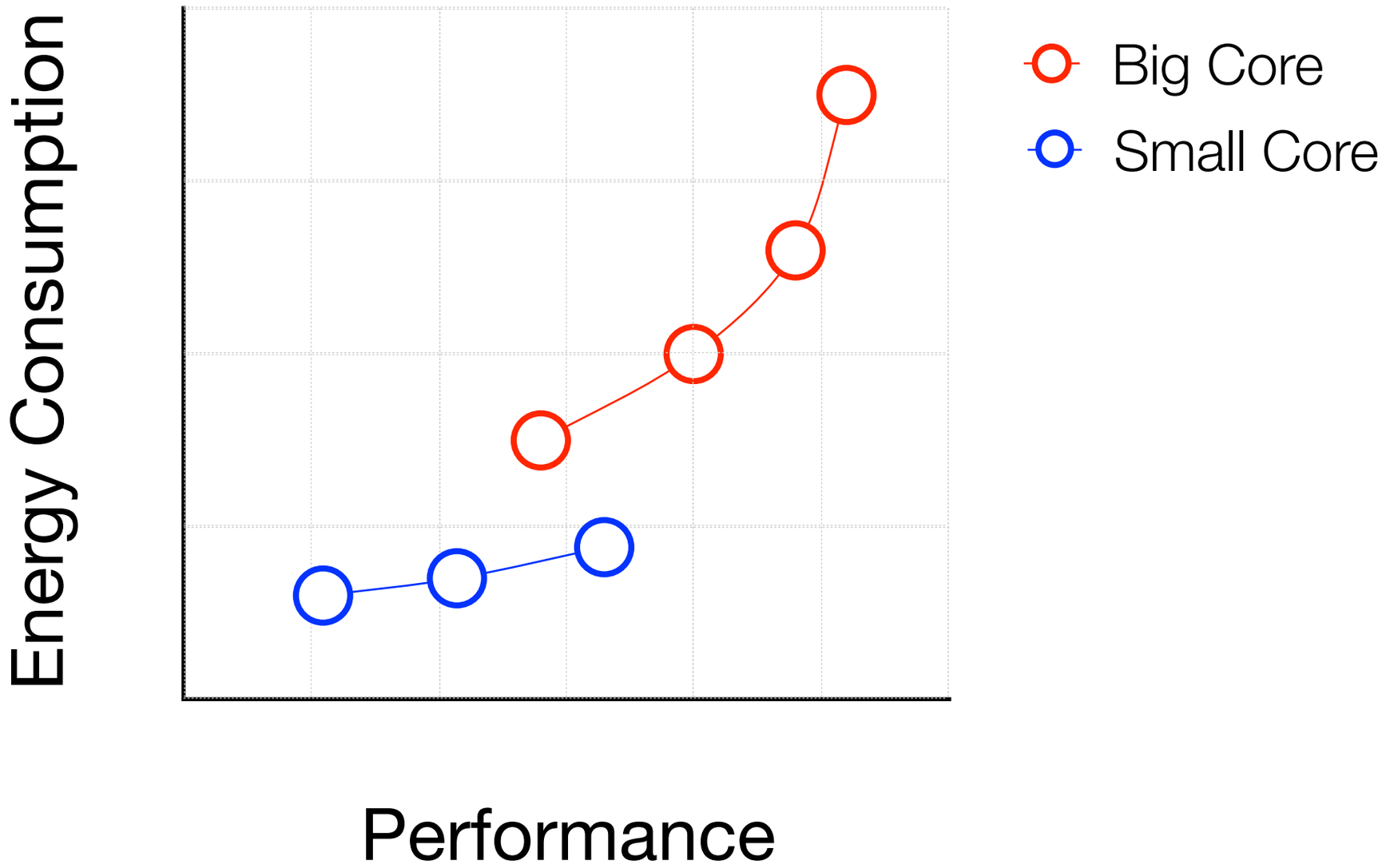
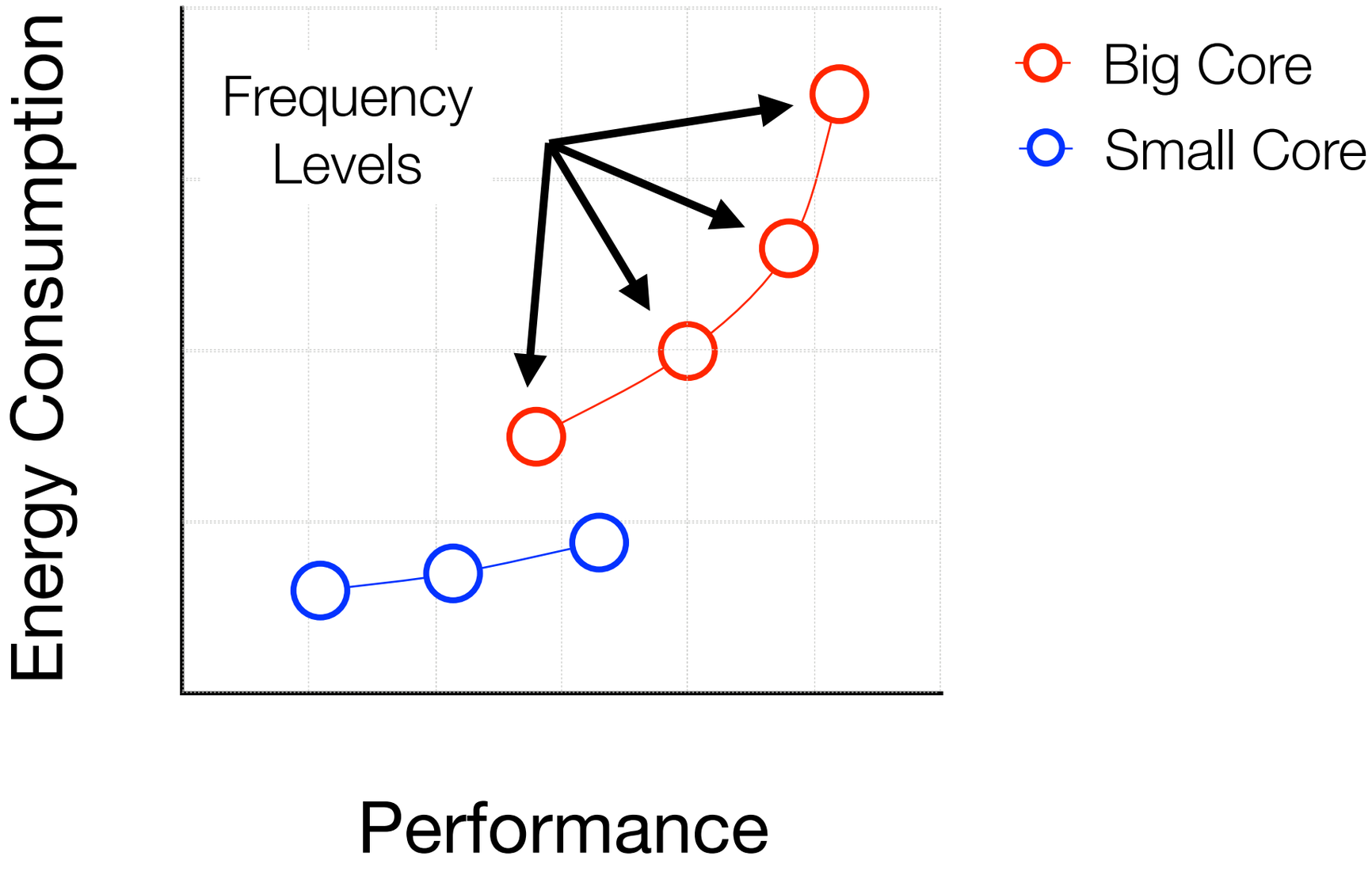


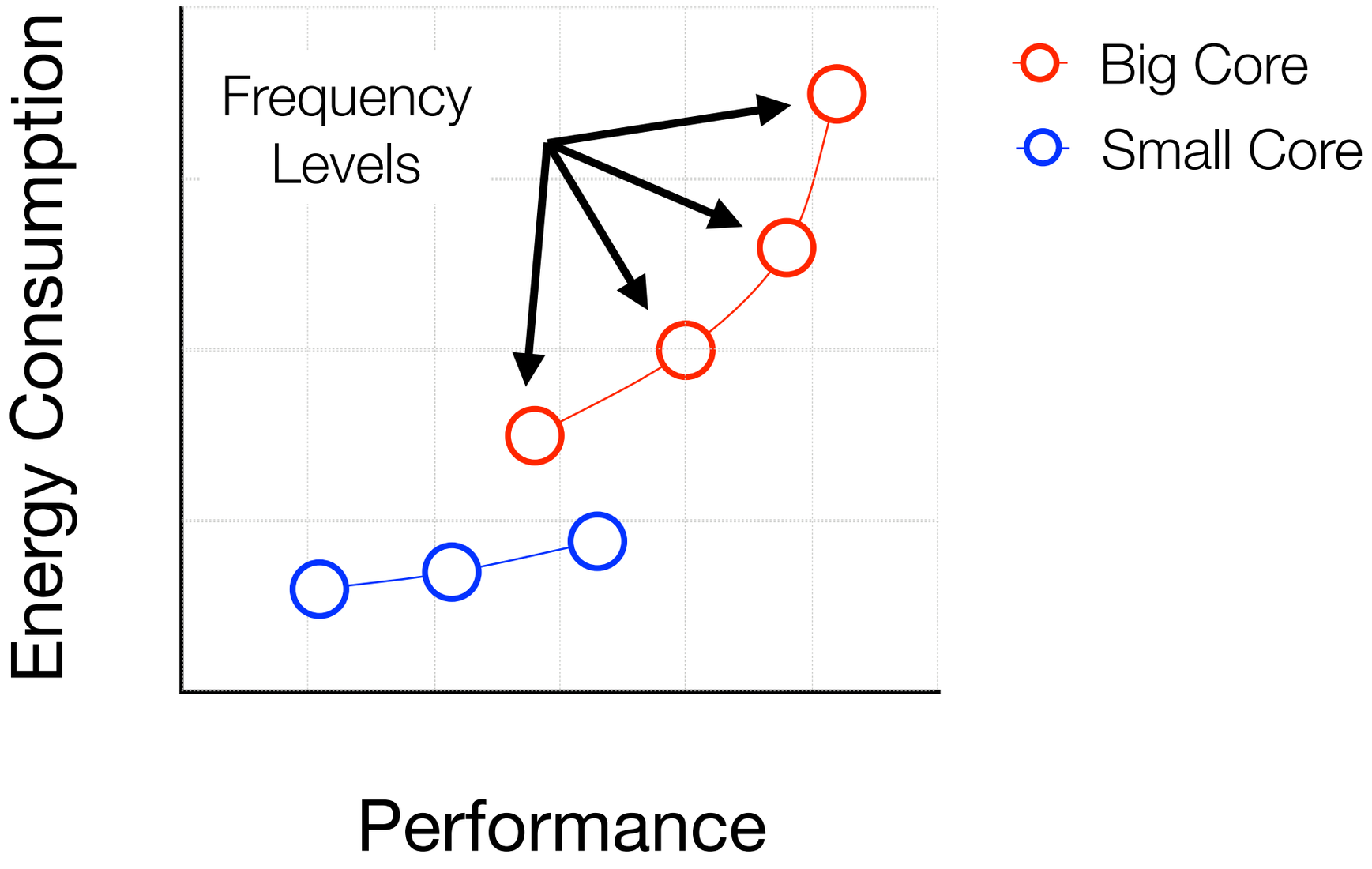
ACMP-based Hardware Substrate

- Asymmetric Chip-multiprocessor, a.k.a., *Big/Little* architecture

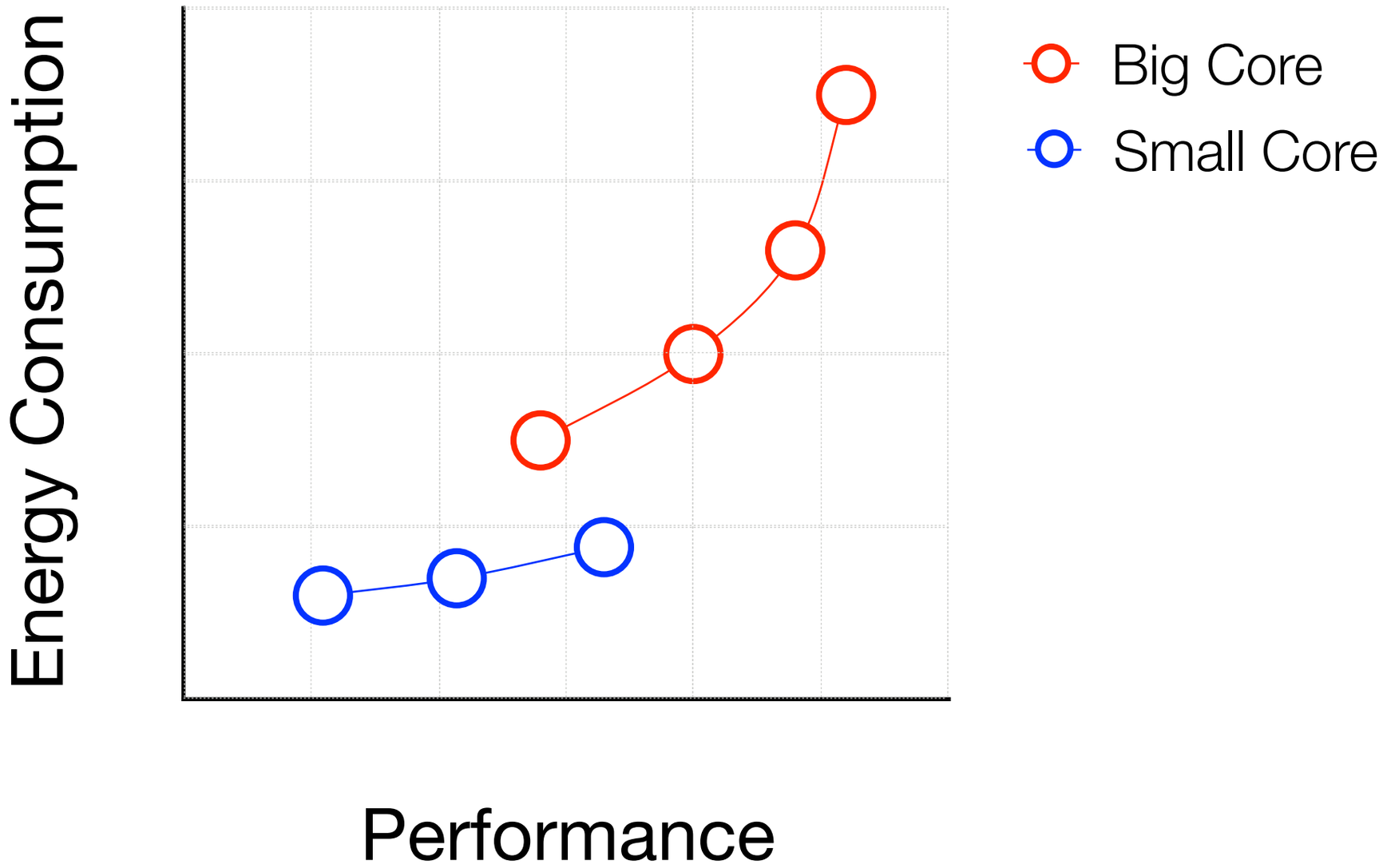


ACMP-based Hardware Substrate

- Asymmetric Chip-multiprocessor, a.k.a., *Big/Little* architecture
- Already used in commodity devices (e.g., Samsung Galaxy S6)



ACMP-based **GreenWeb** Runtime



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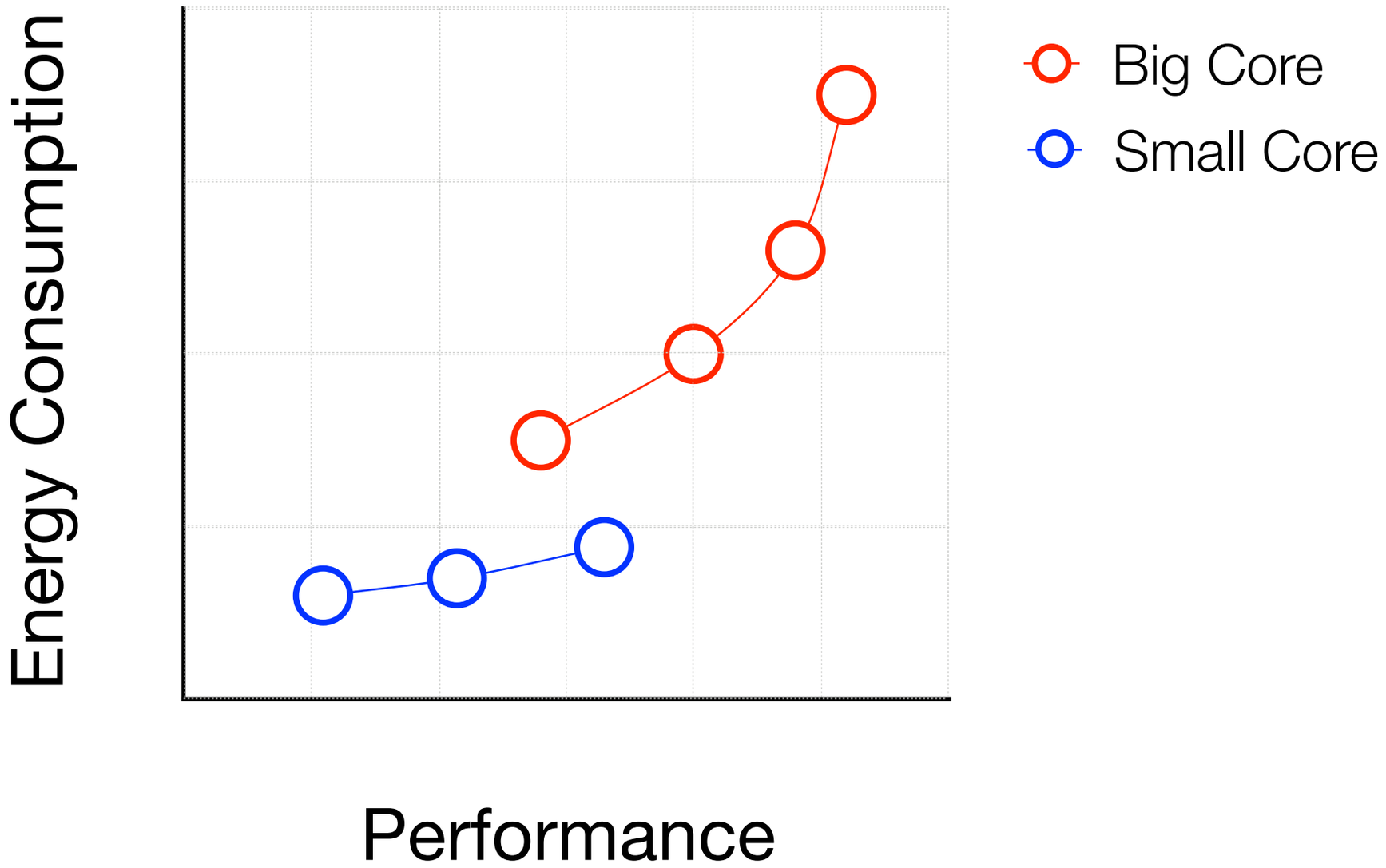
- Provide just enough energy to meet QoS constraints



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div {ontouchend: latency, 16 ms}
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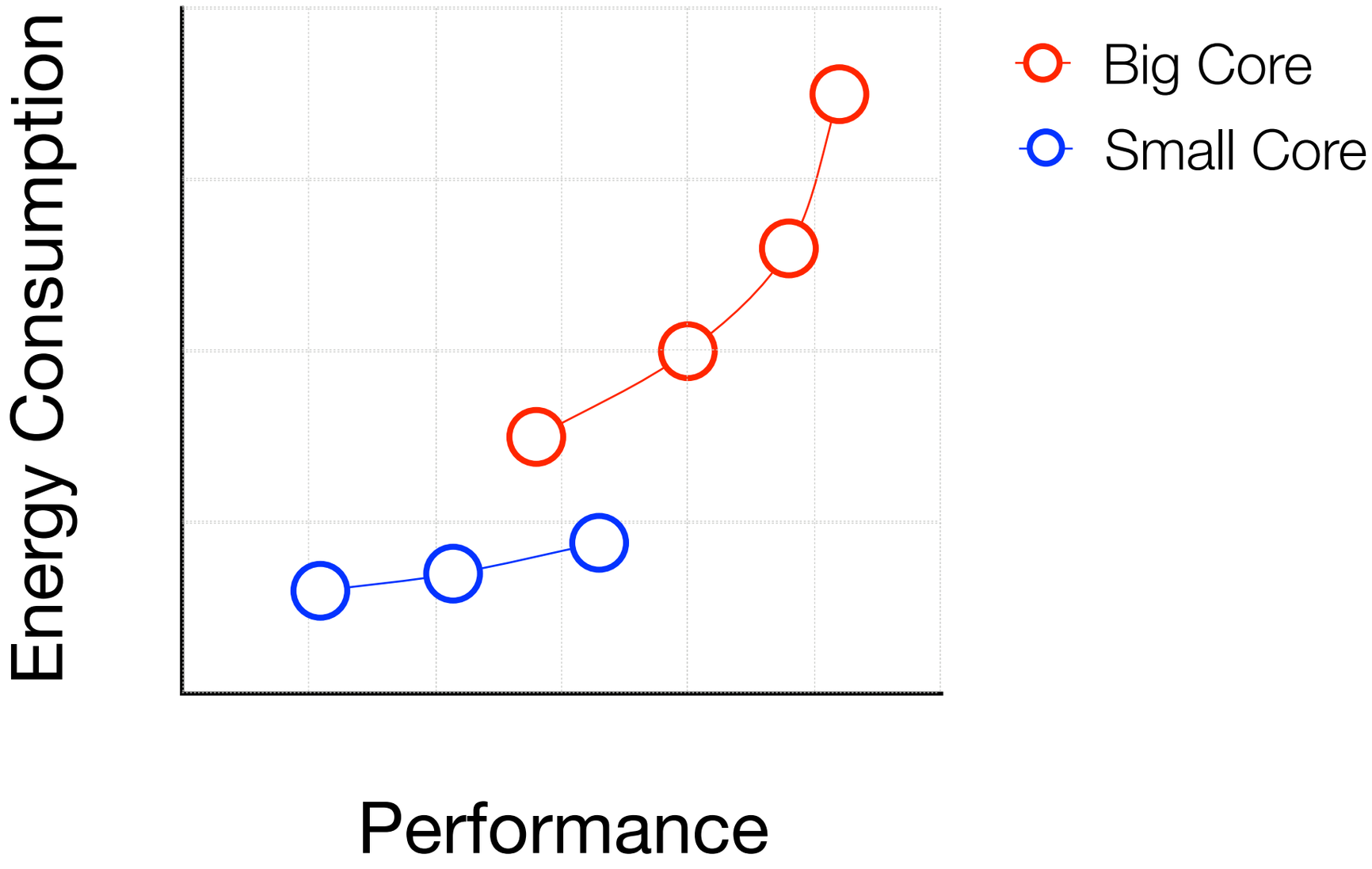

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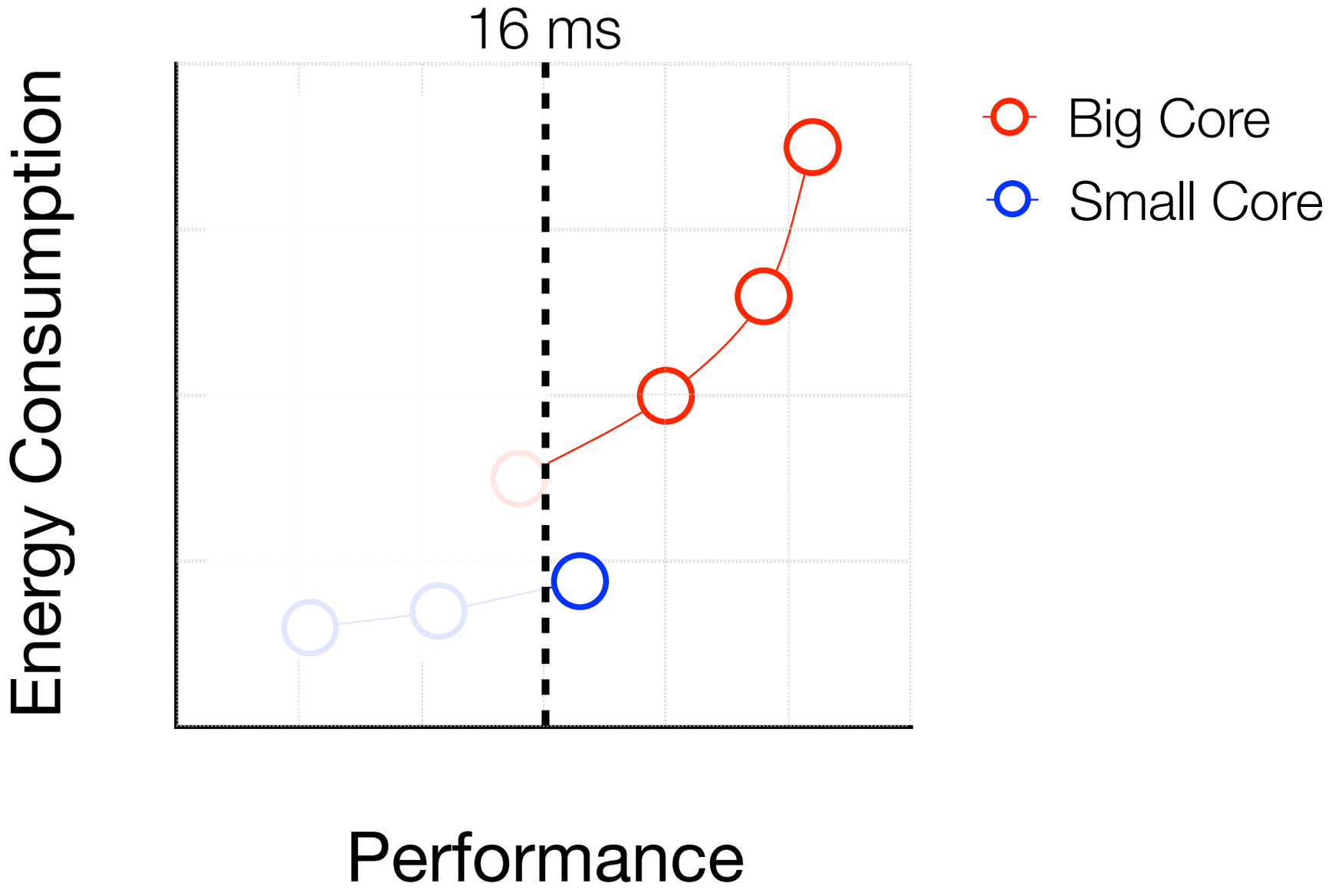

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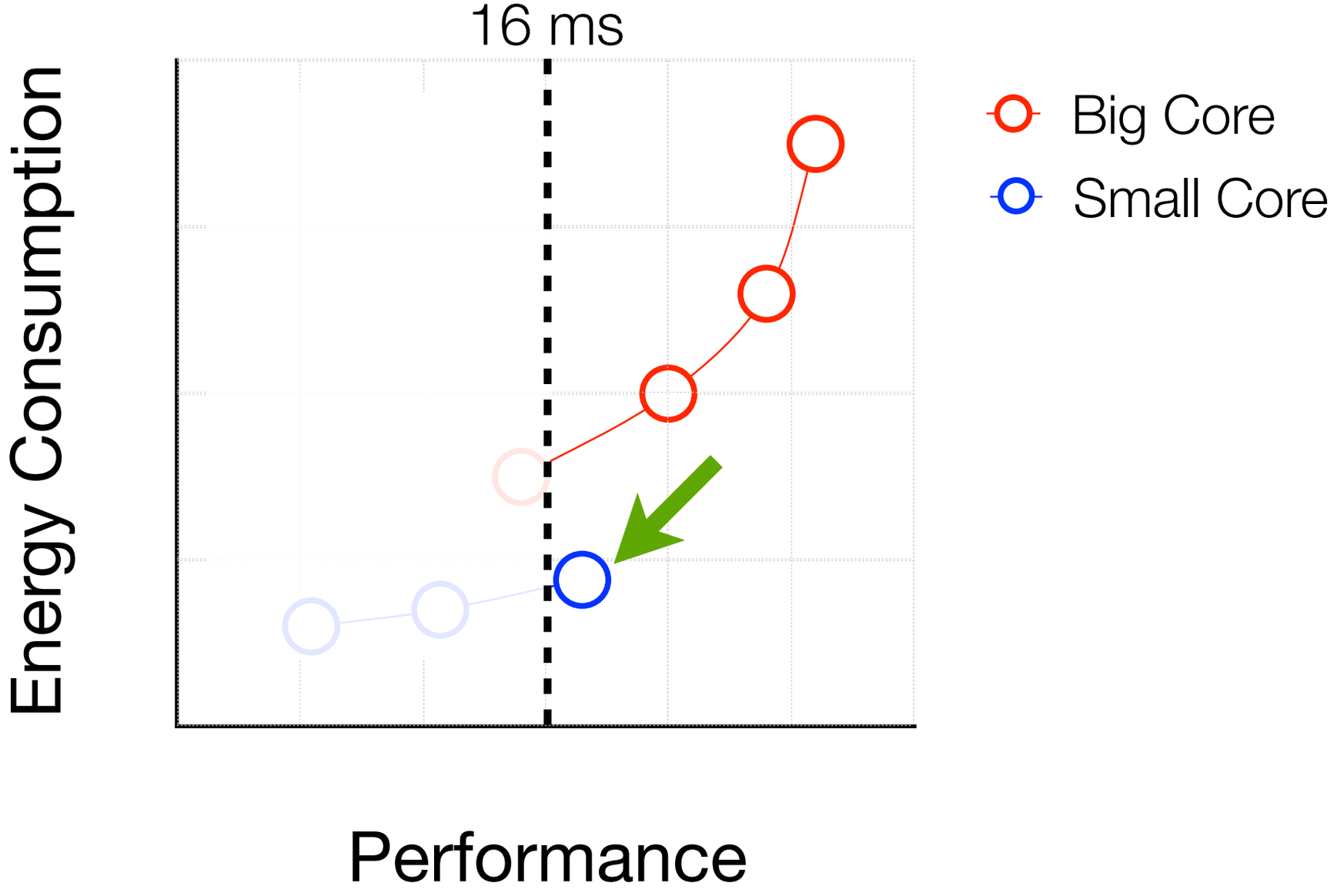

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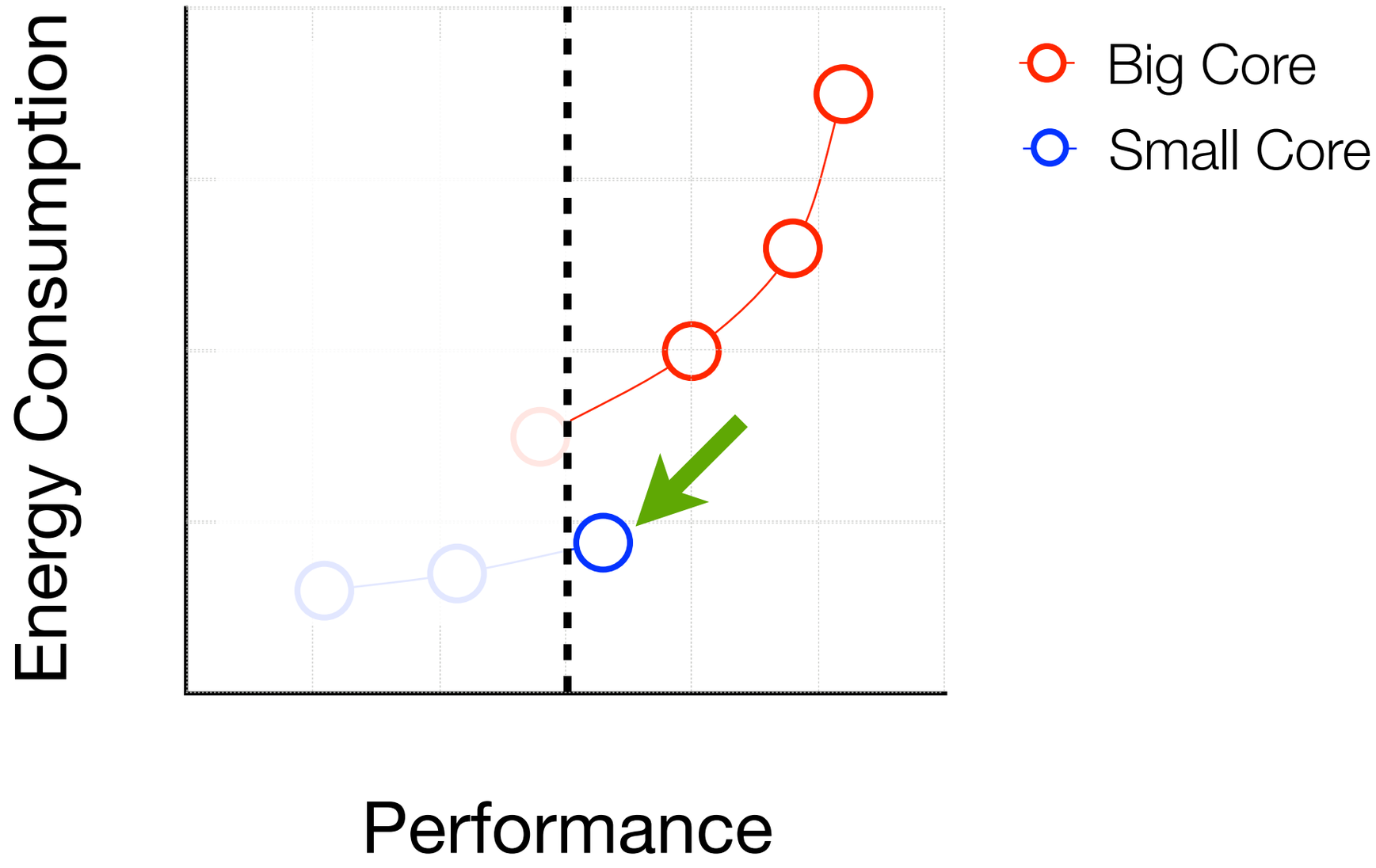

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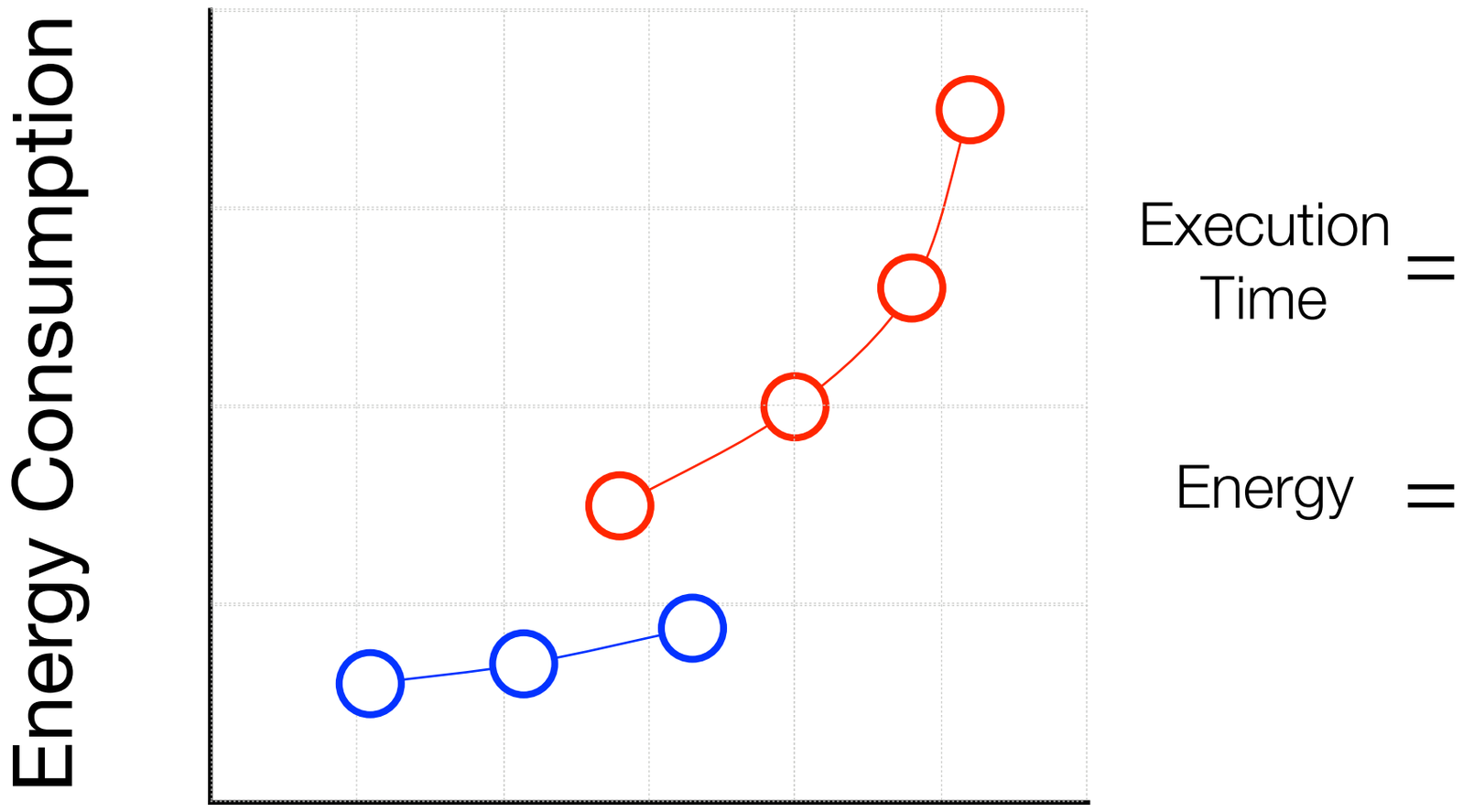

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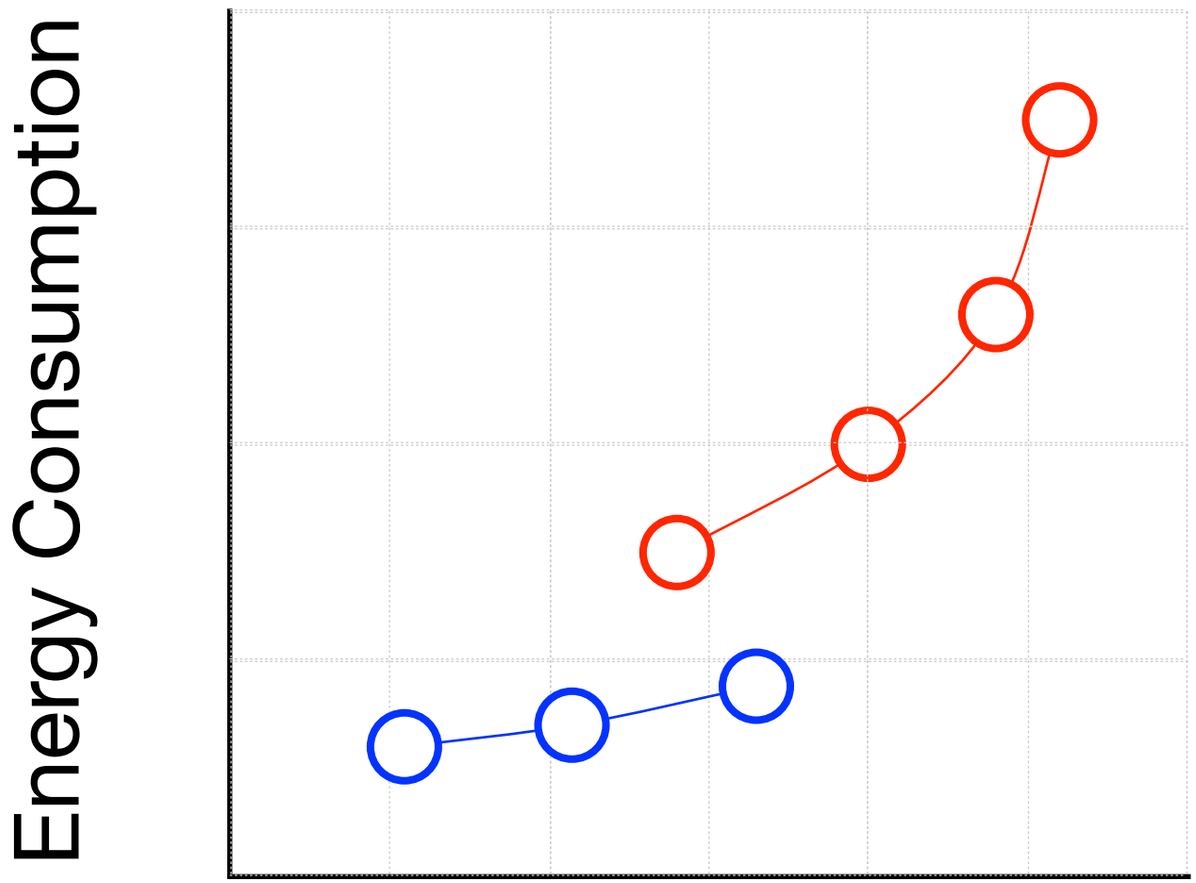

$$\text{Execution Time} = T_{memory} +$$

$$\text{Energy} =$$

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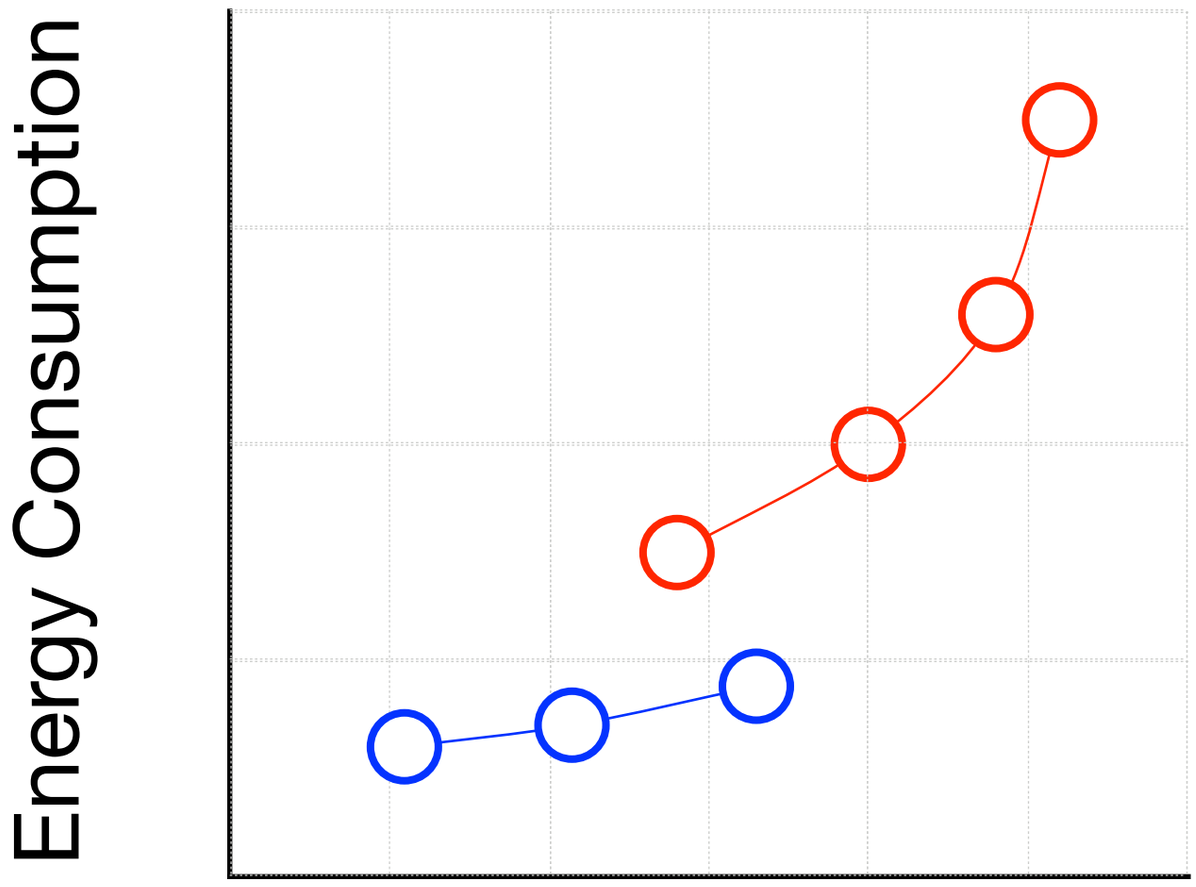

$$\text{Execution Time} = T_{memory} + T_{cpu}$$

$$\text{Energy} =$$

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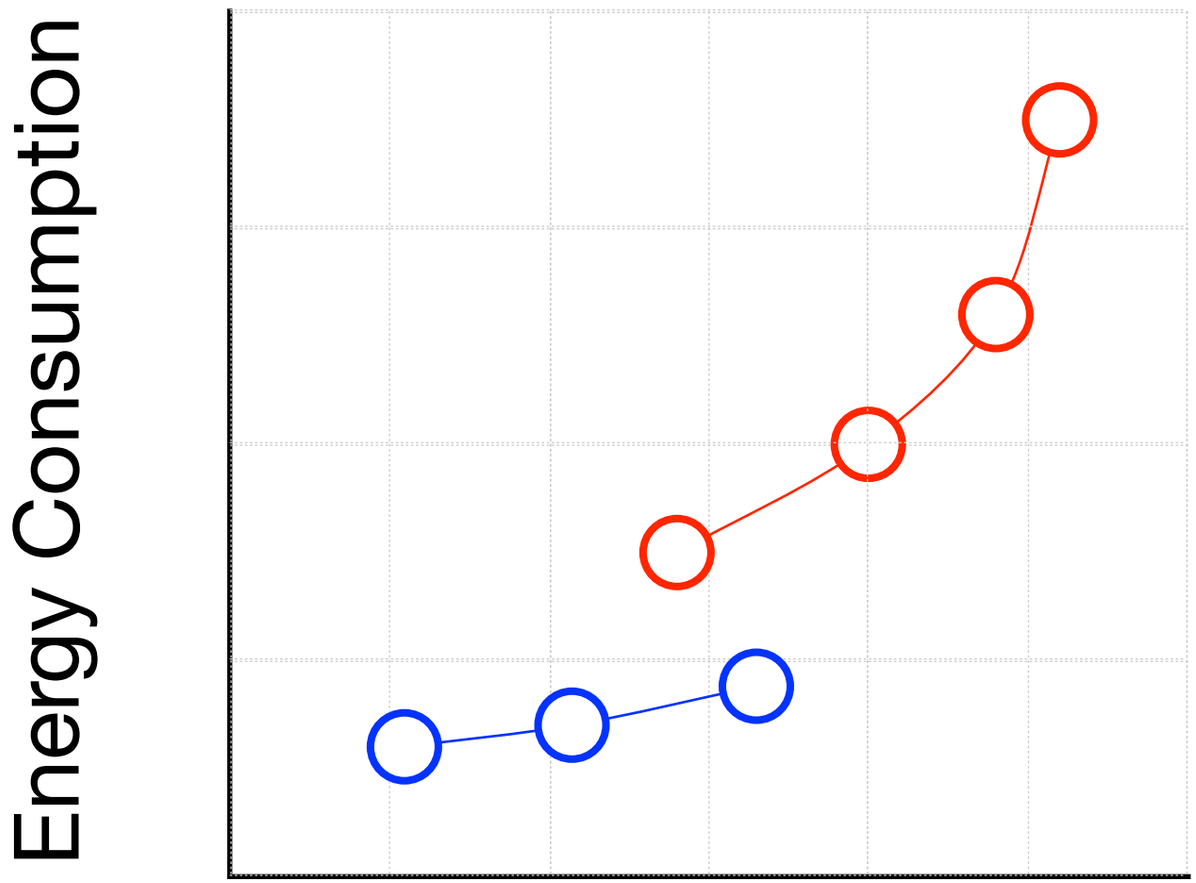

$$\text{Execution Time} = T_{memory} + N_{cycles} / f$$

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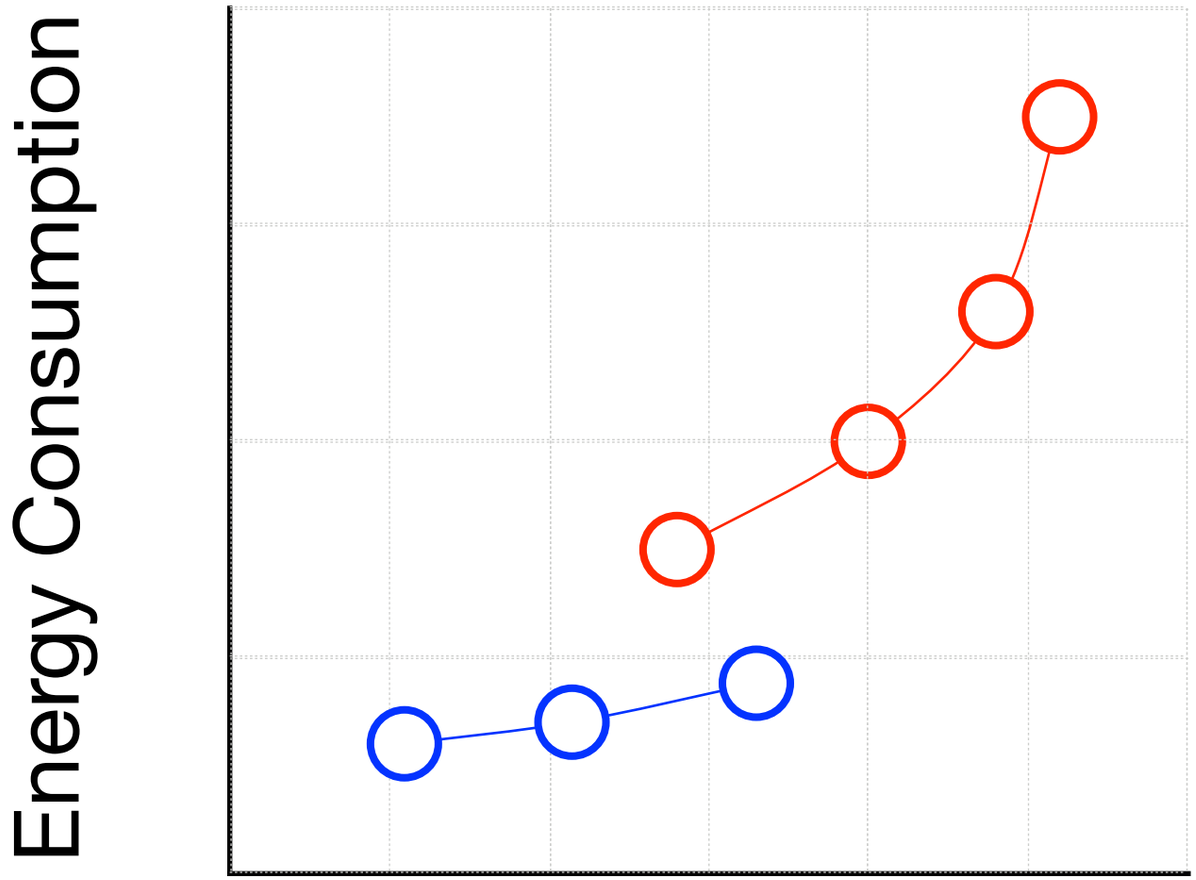

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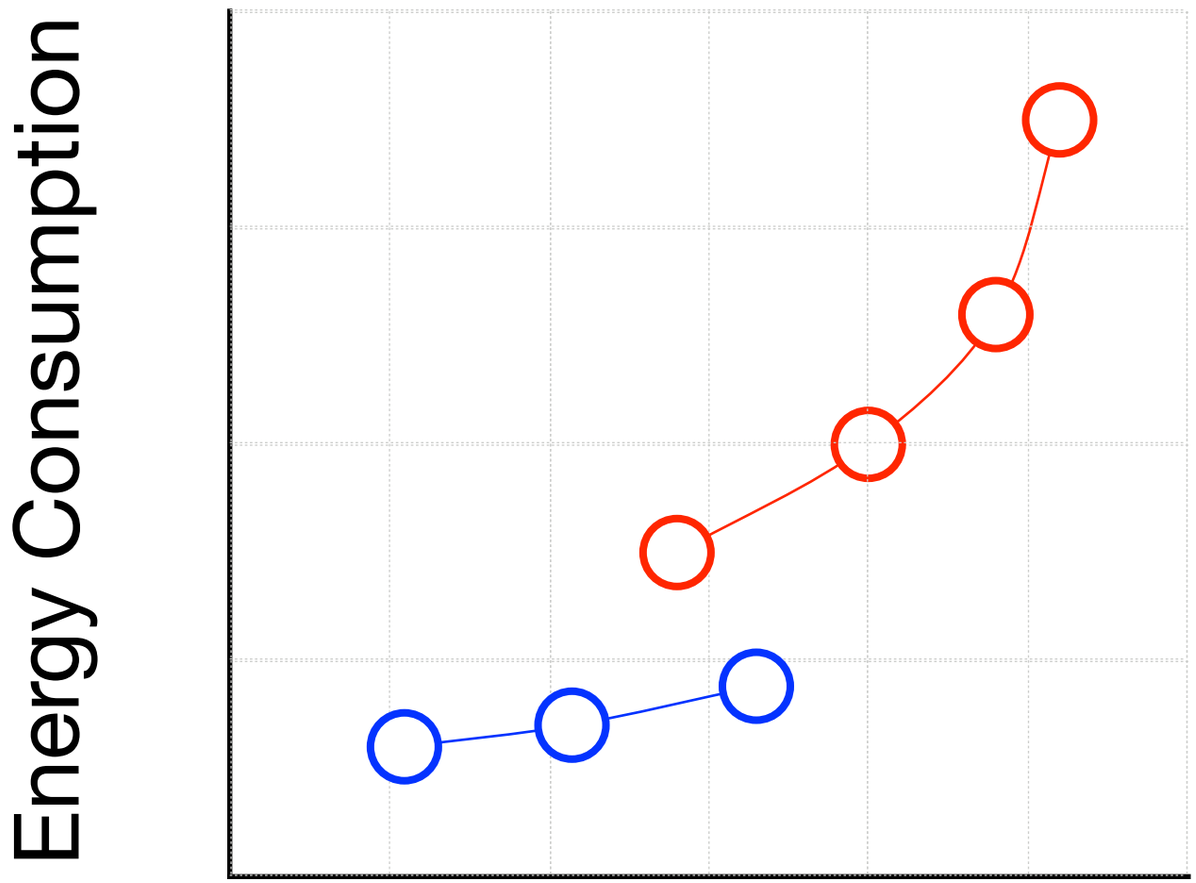

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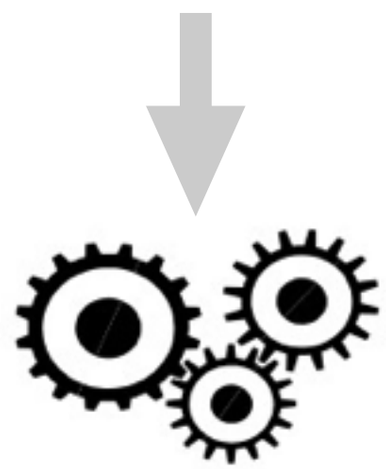
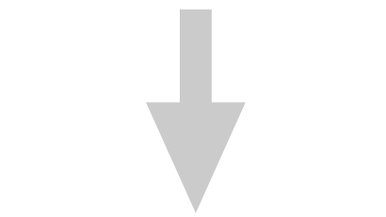
GreenWeb: Language for Energy-Efficiency





- 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.

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

Implementation incorporated into Chrome running on Android.

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MOSAIC

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

Evaluation

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

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- Metrics
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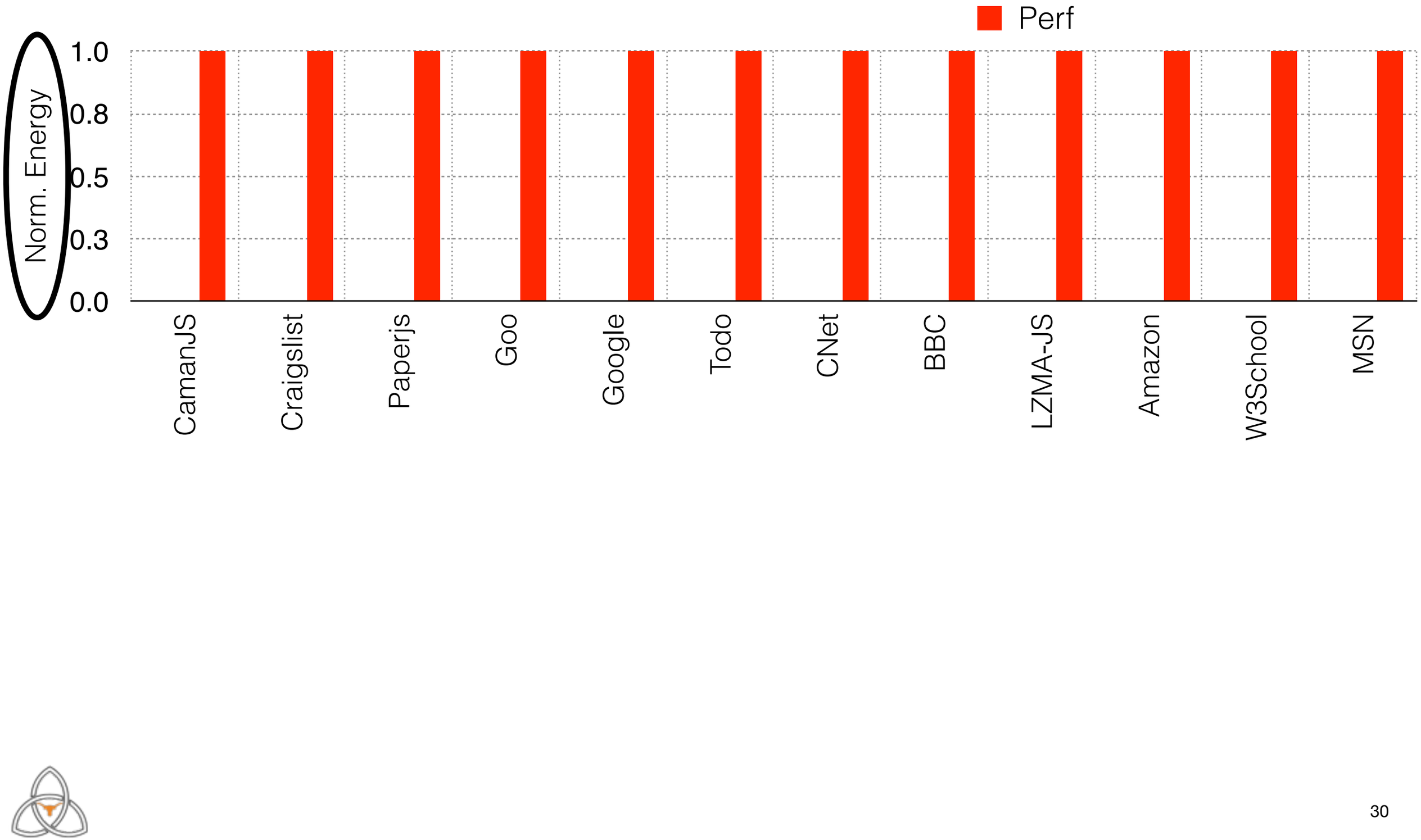
- Applications
  - Top webpages (e.g., www.amazon.com)
  - Web Apps based on popular frameworks (e.g., Todo List)

Evaluation Results



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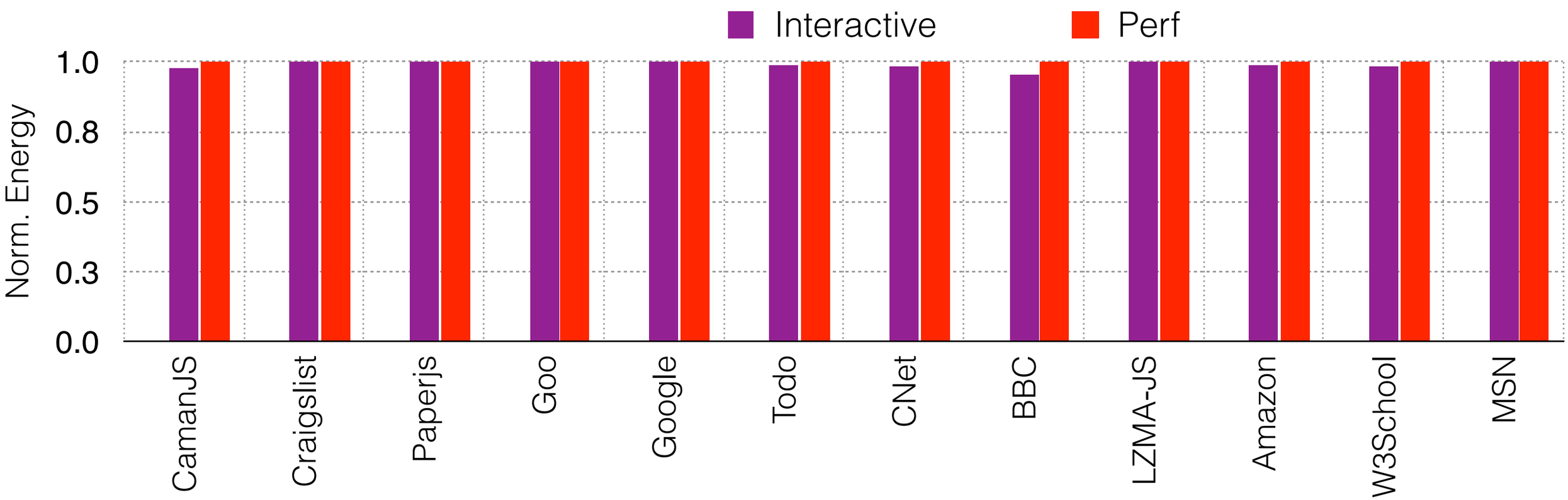

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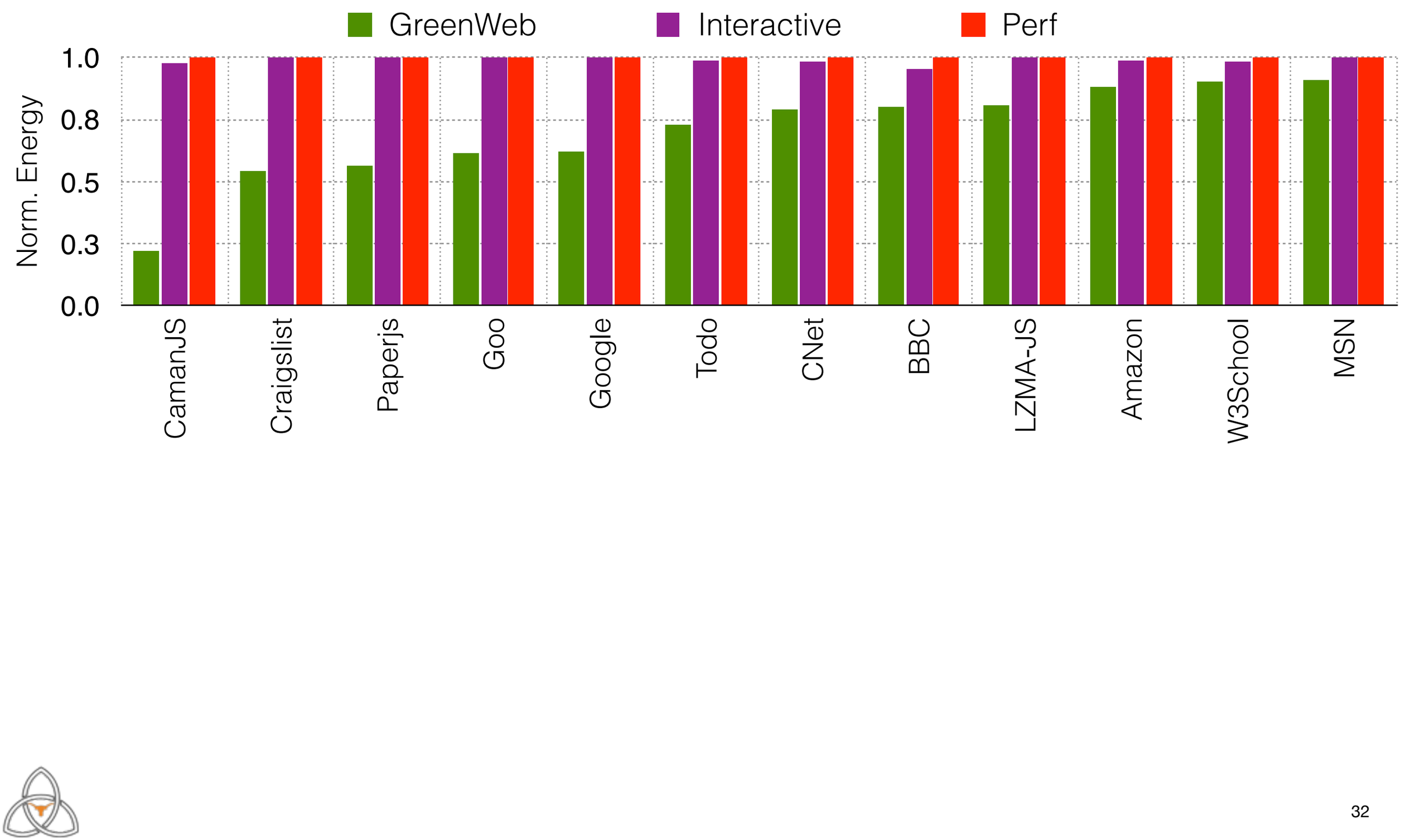

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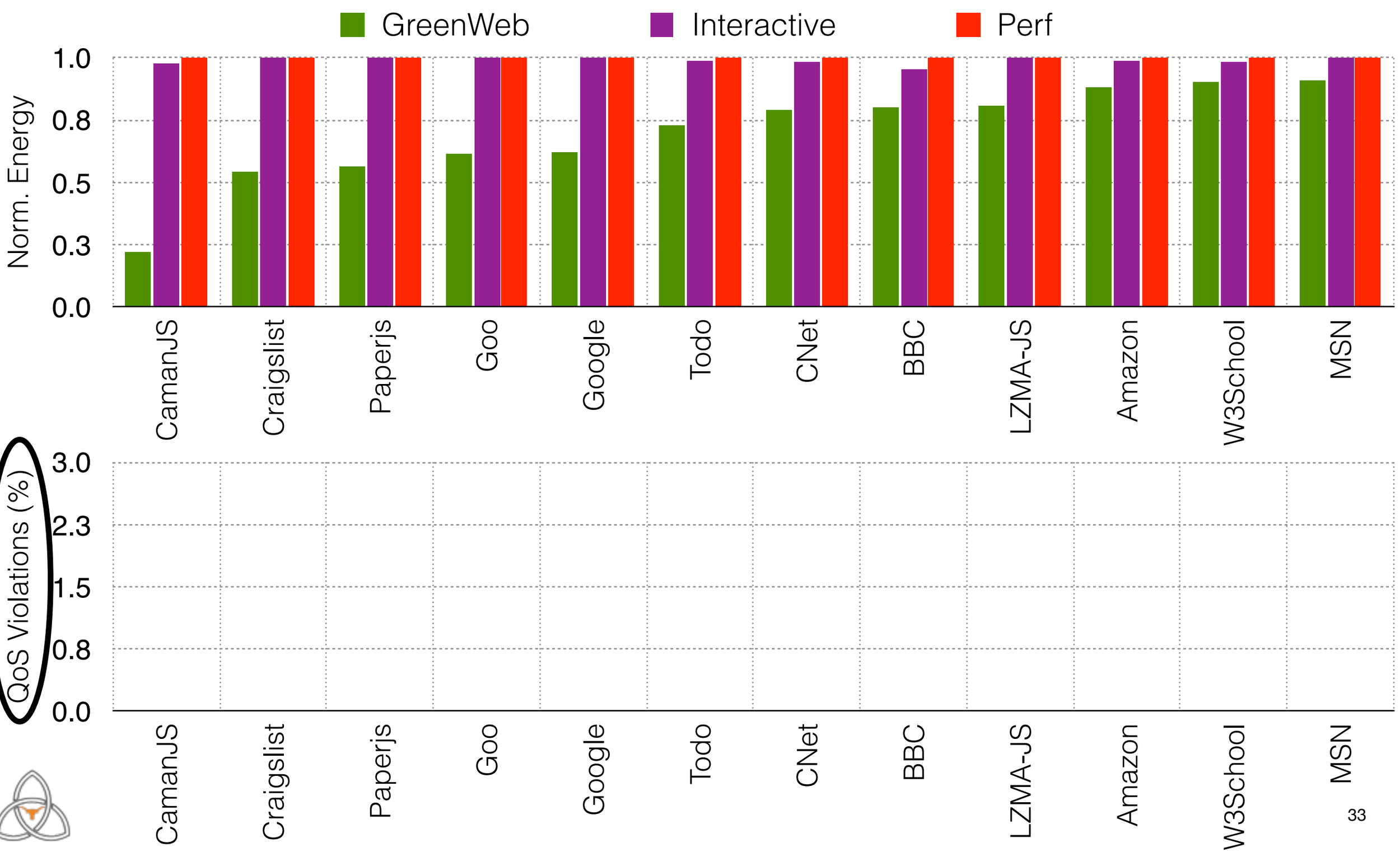

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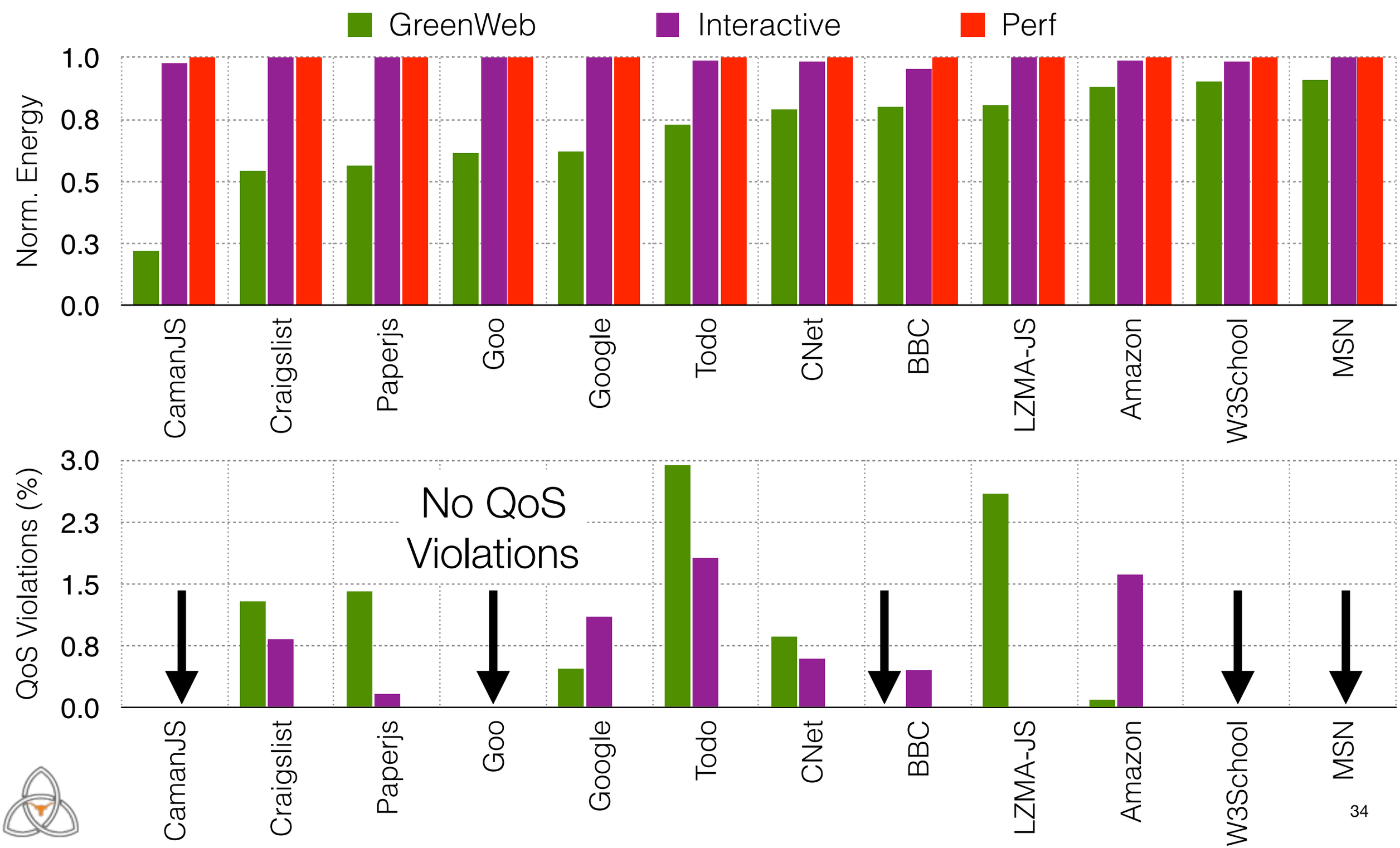

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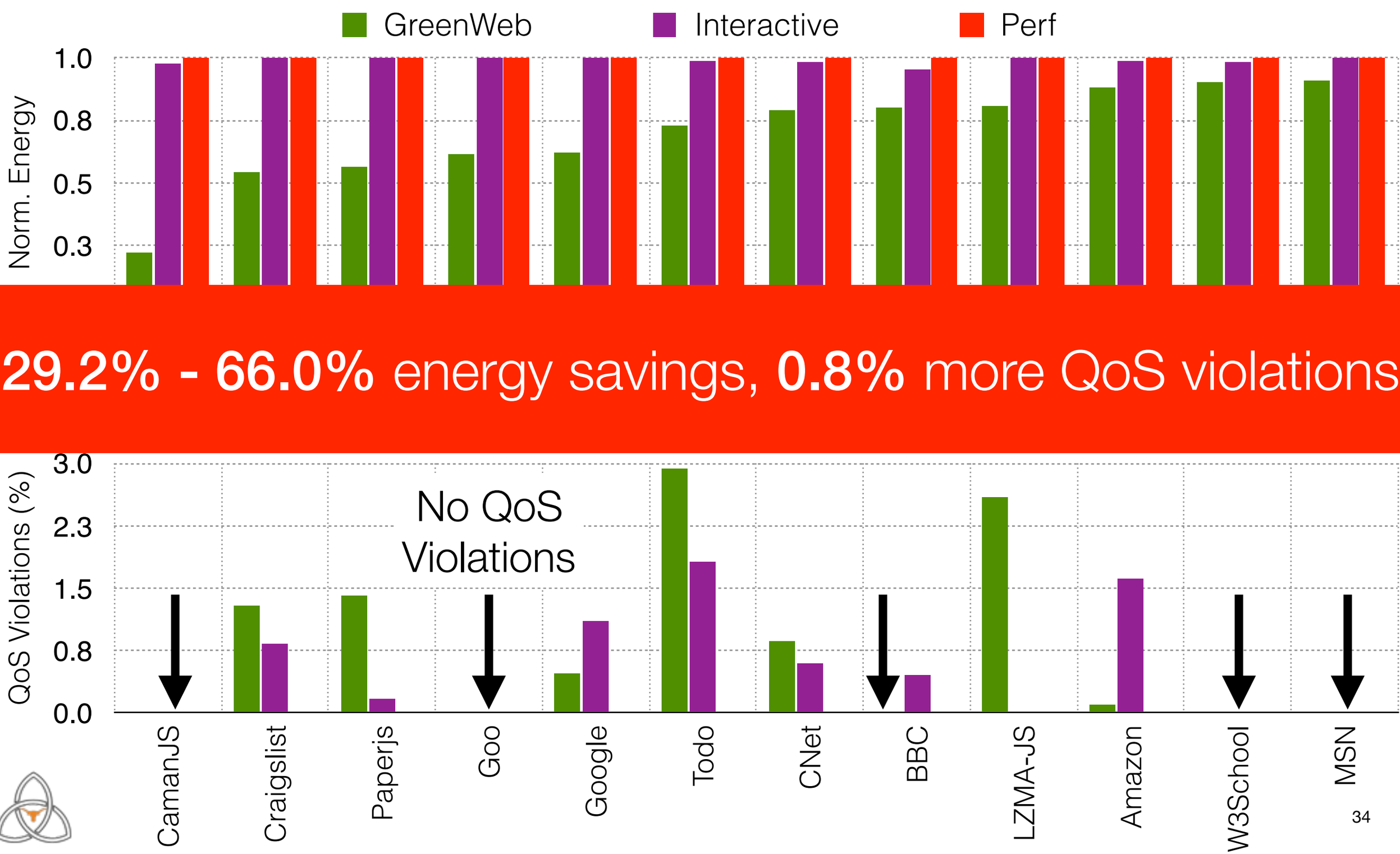

29.2% - 66.0% energy savings, **0.8%** more QoS violations

GreenWeb

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

GreenWeb

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

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

wattwiseweb.org

GreenWeb:

Language Extensions for Energy-Efficient Mobile Web Computing

Yuhao Zhu
The University of Texas at Austin
with Vijay Janapa Reddi