Event-Based Scheduling for Energy-Efficient Quality of Service (eQoS) in Mobile Web Applications

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TRINITY

Responsiveness

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- 100 ms latency is the limit for having users feel the system is reacting responsively [Miller 1968; Card et al. 1991]

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- Amazon found every 100 ms of latency costs them 1% in sales per year [Source: Amazon]

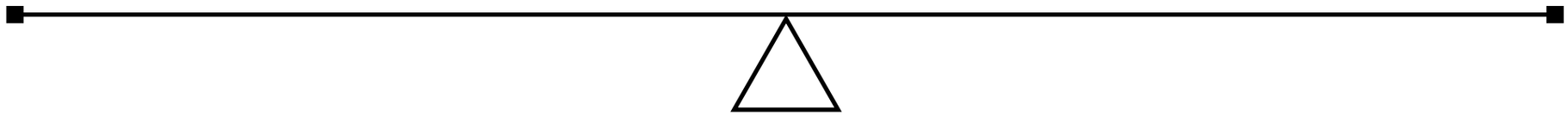
Responsiveness

Energy-Efficiency

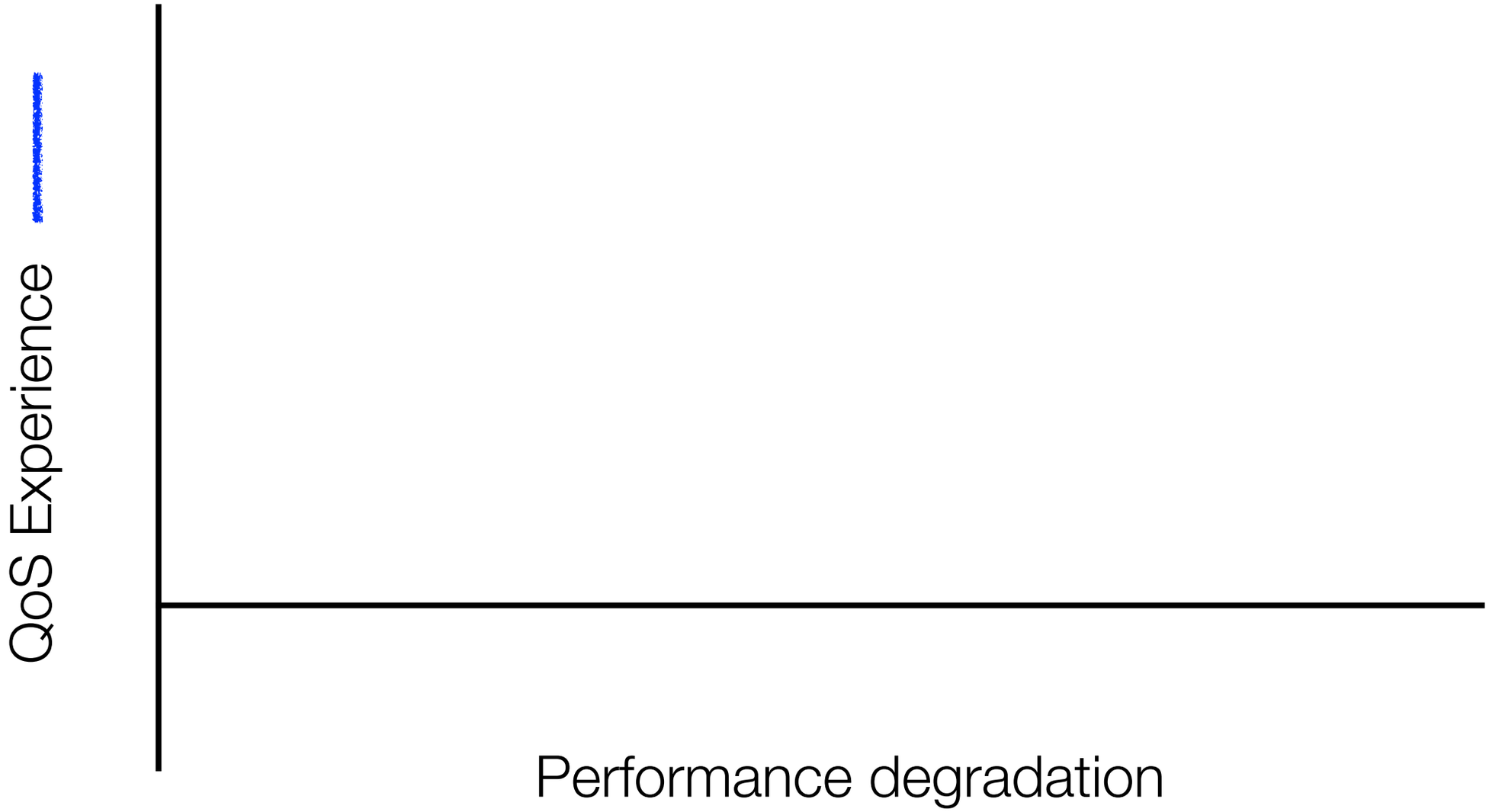
Responsiveness

Conflicting requirements

Energy-Efficiency



Making a Calculated Trade-off



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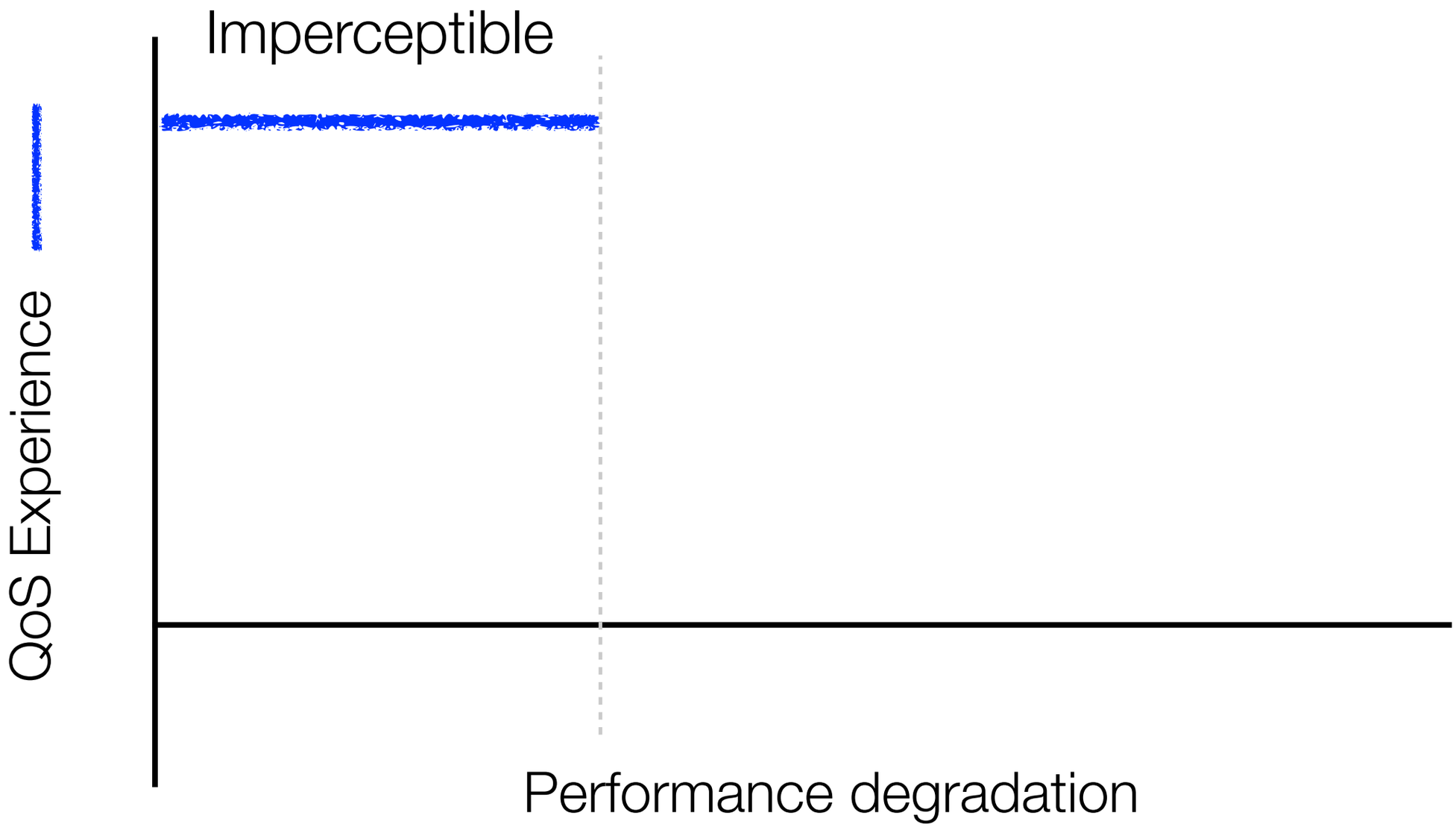

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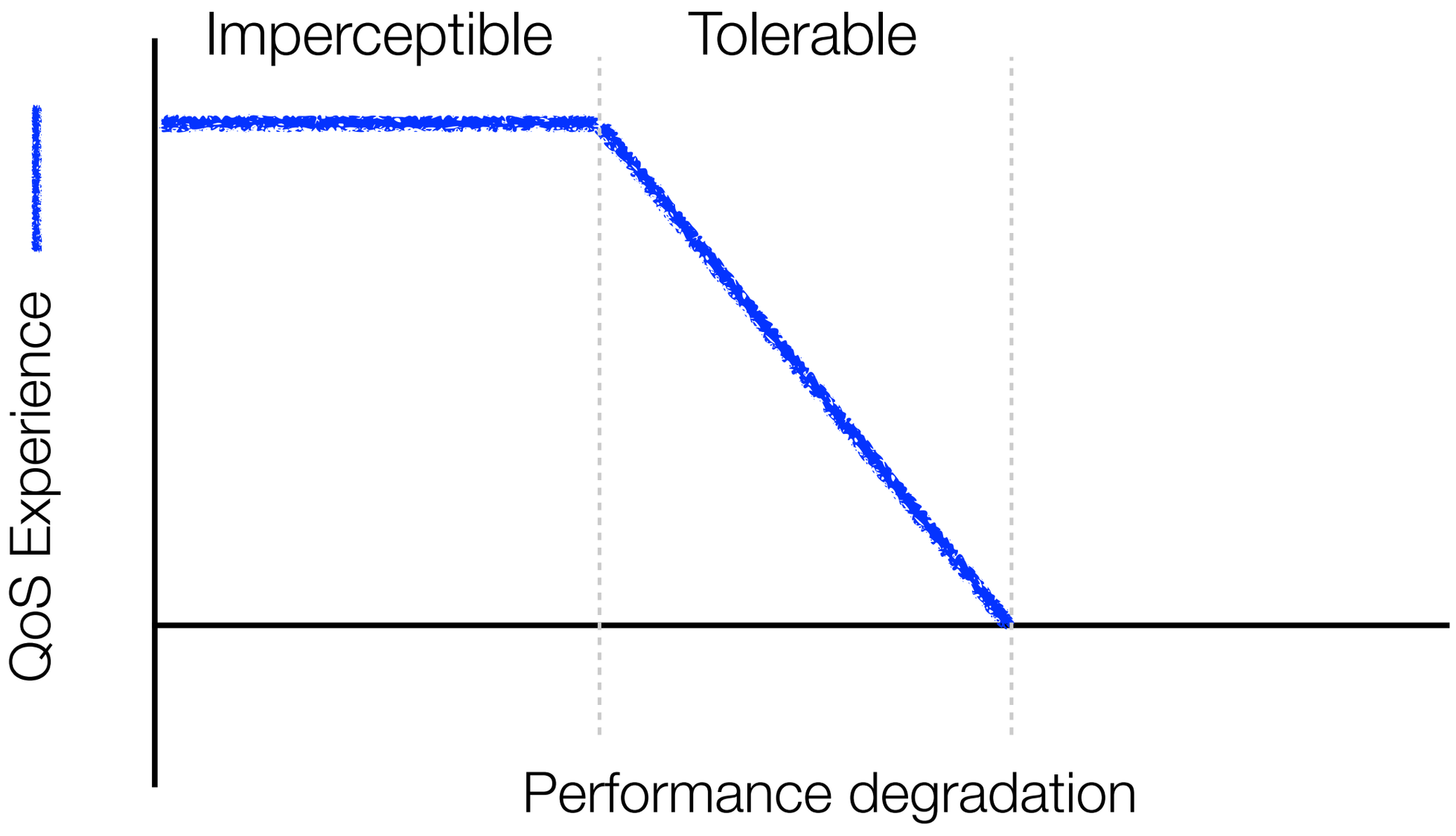

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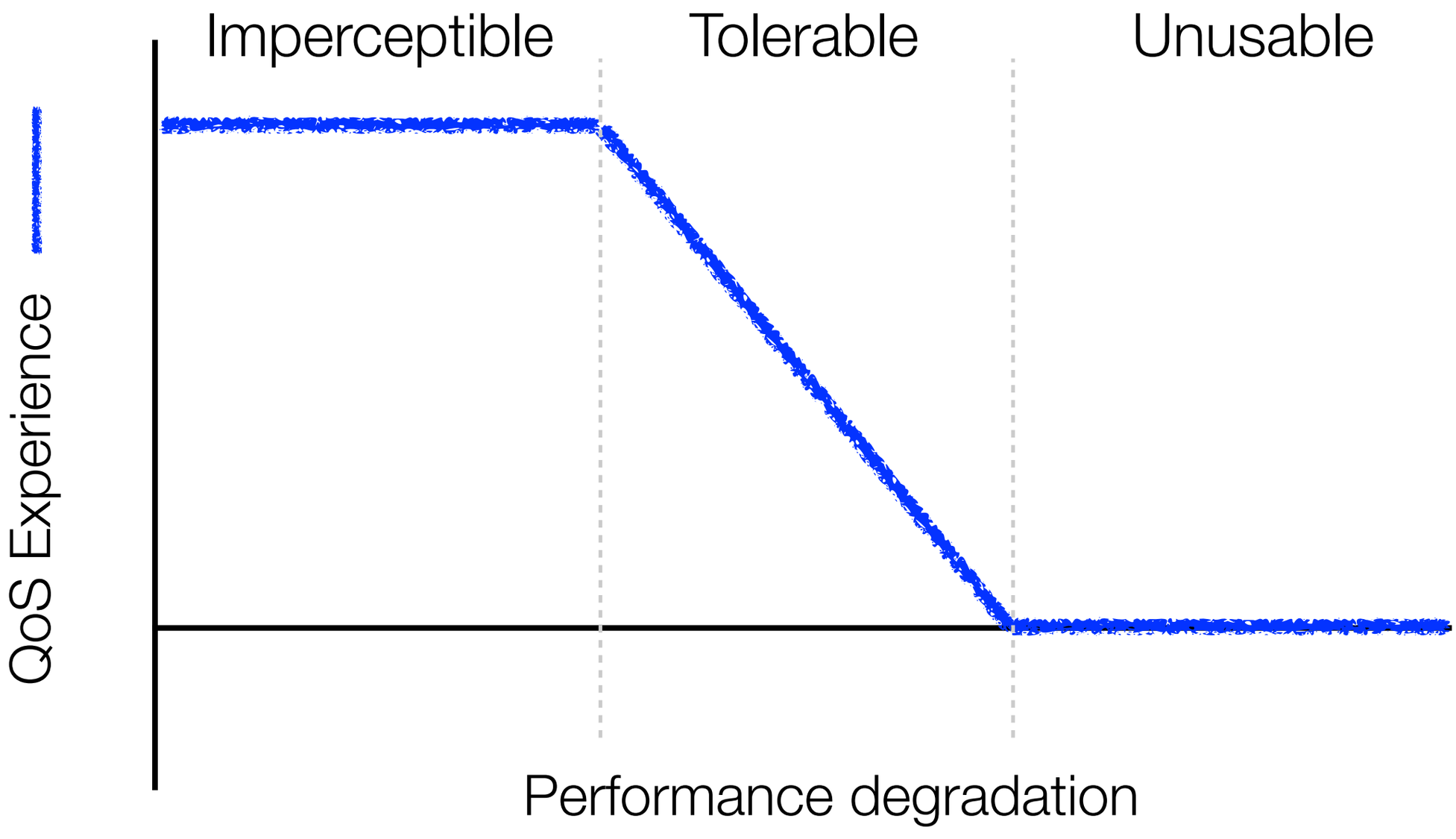

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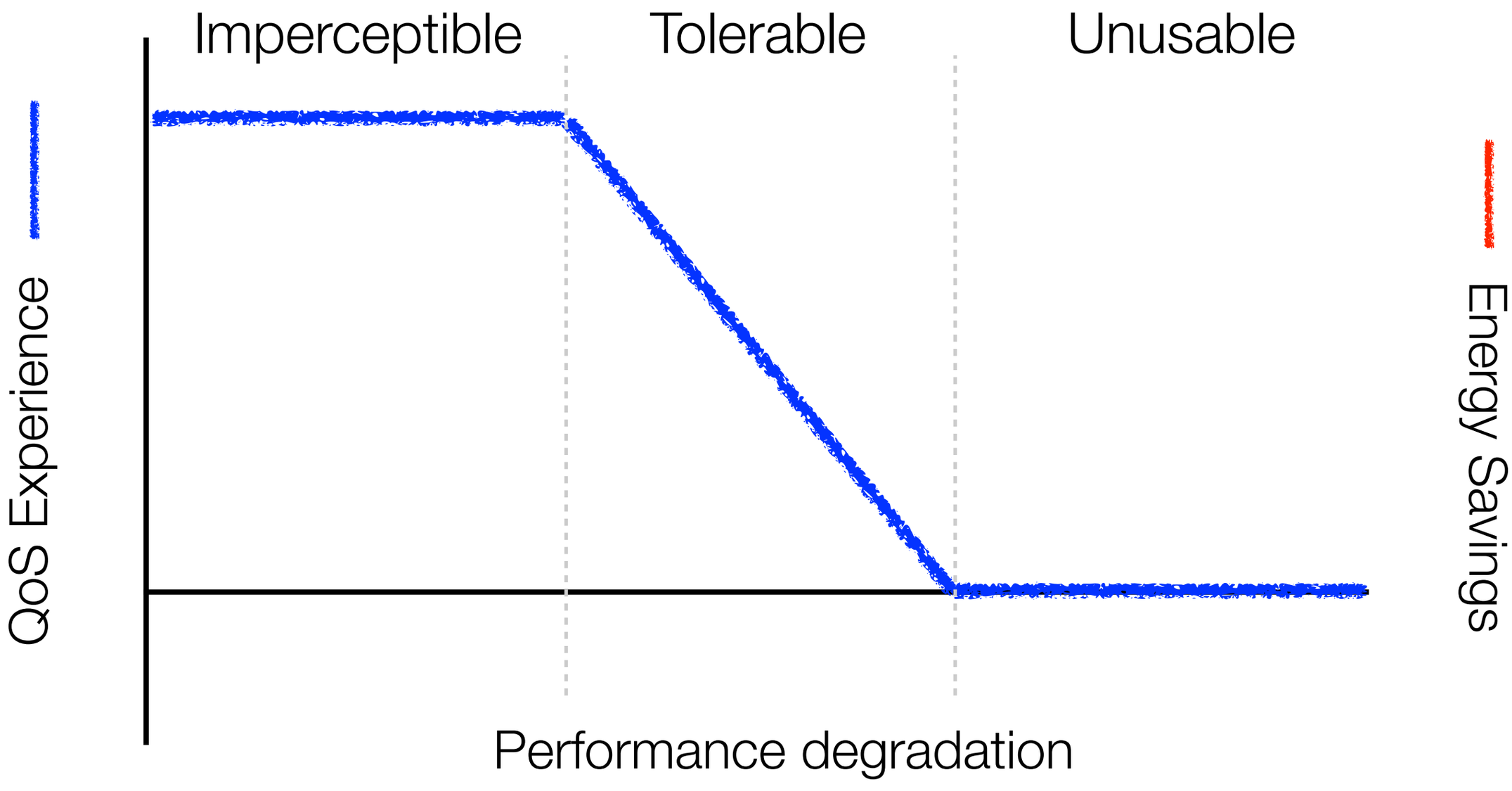

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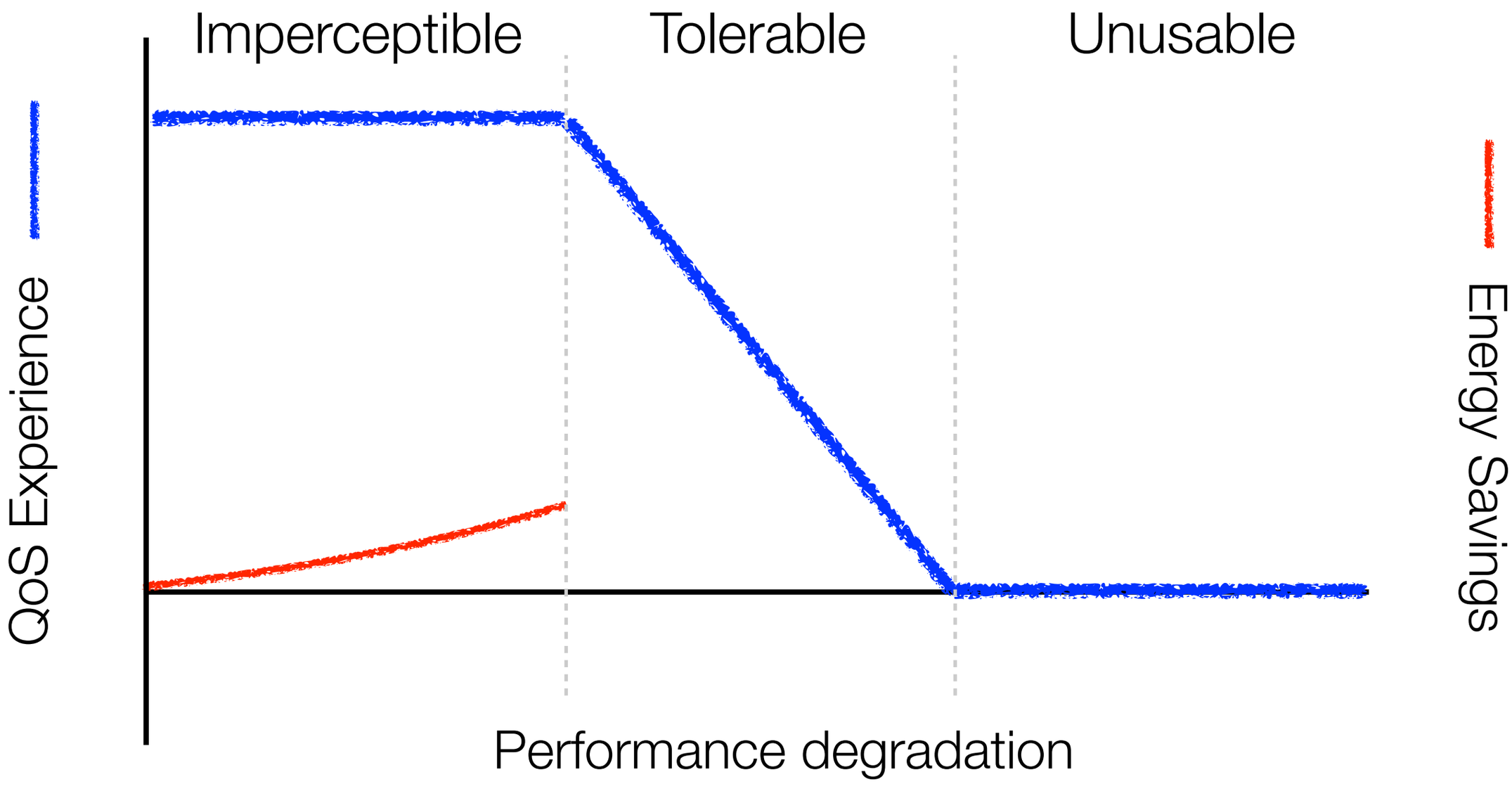

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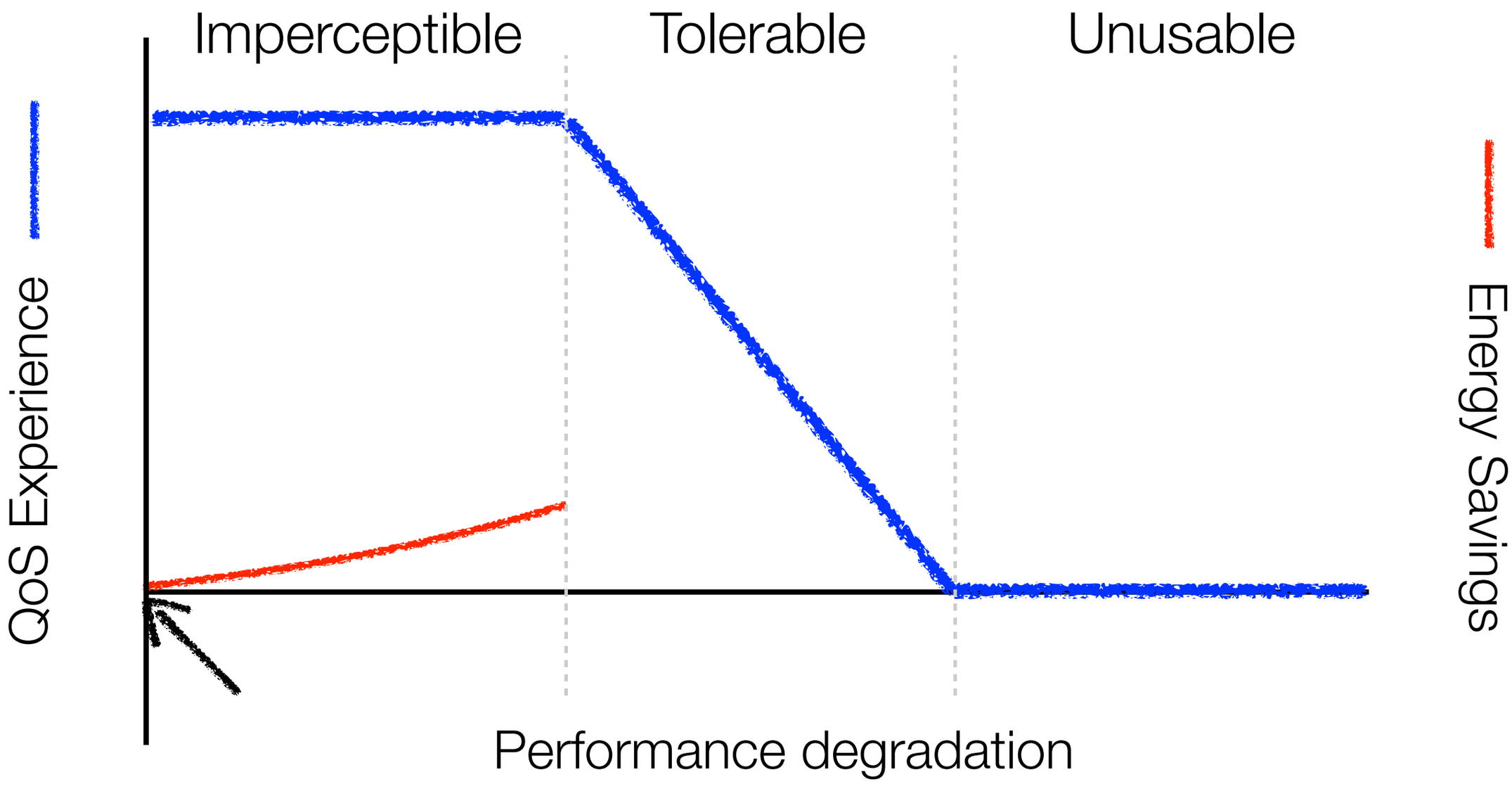

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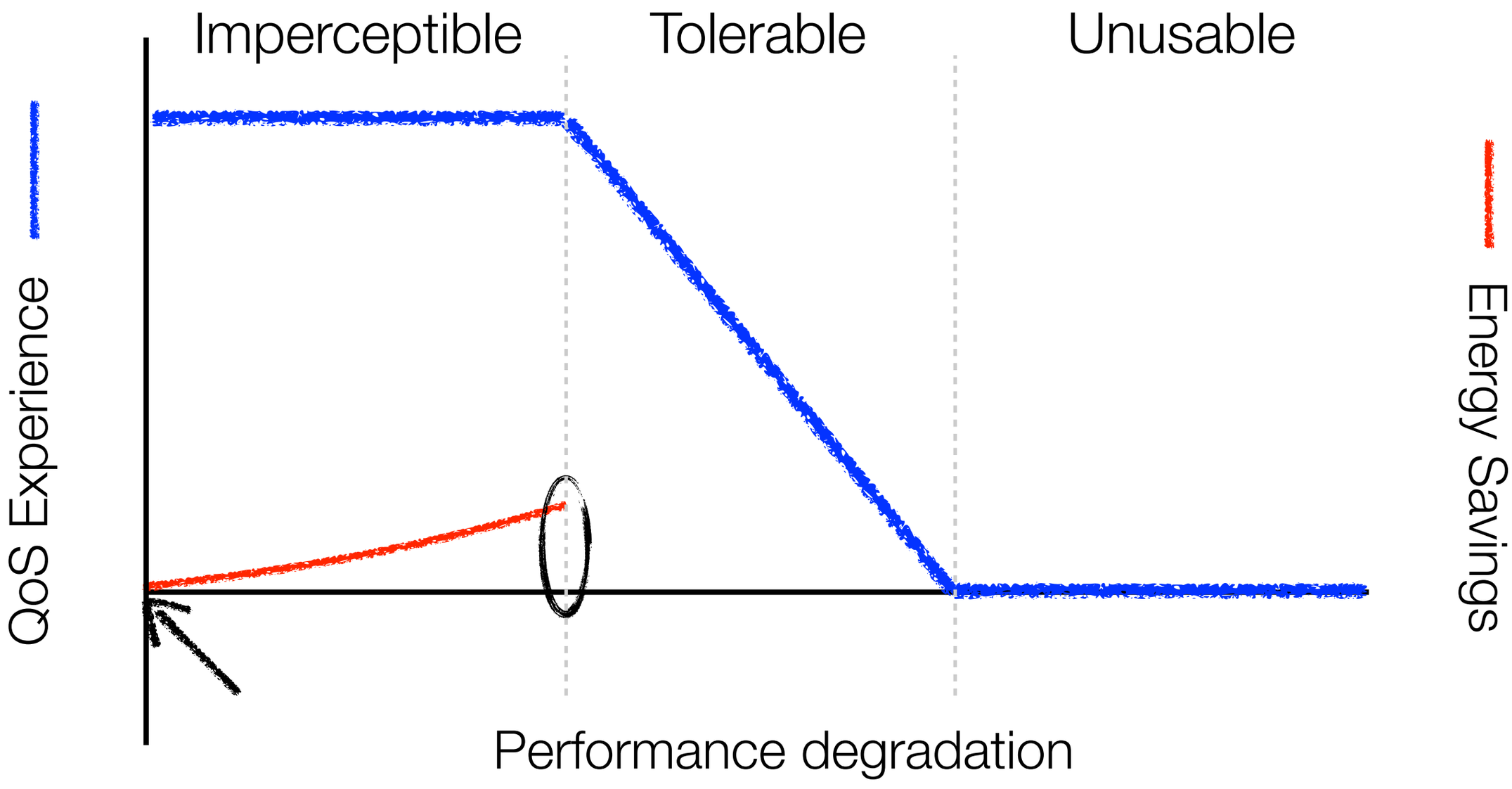

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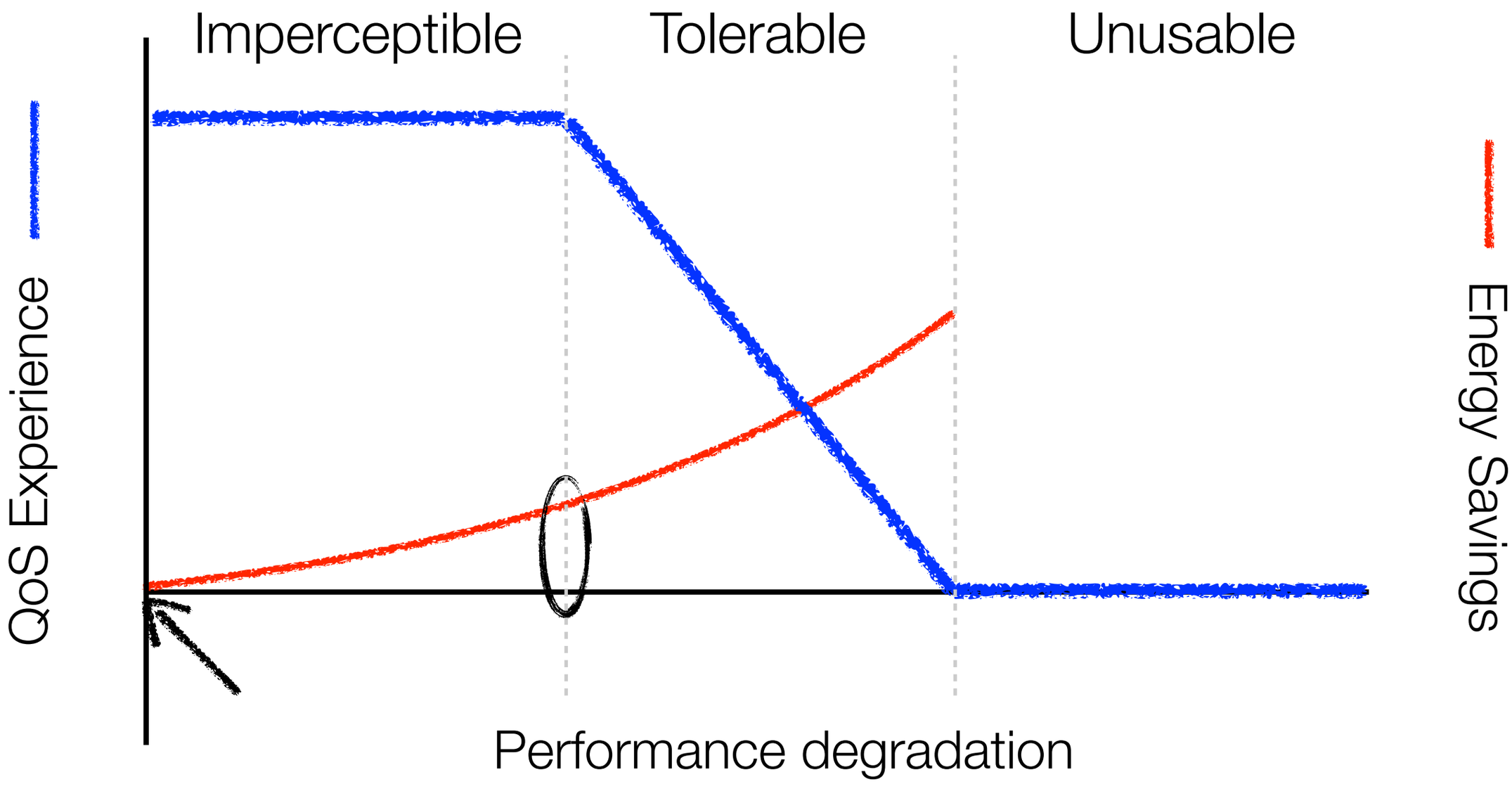

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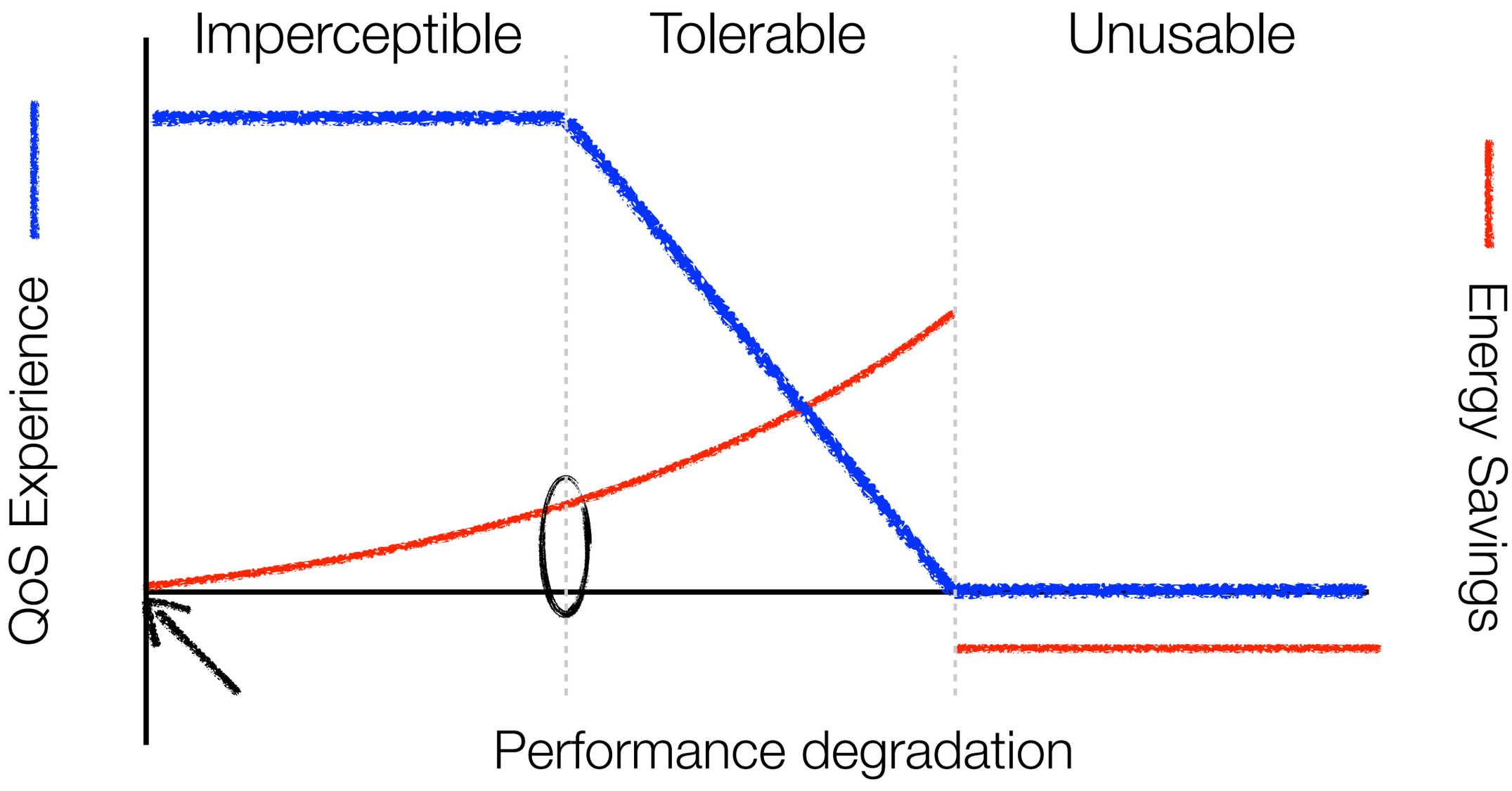
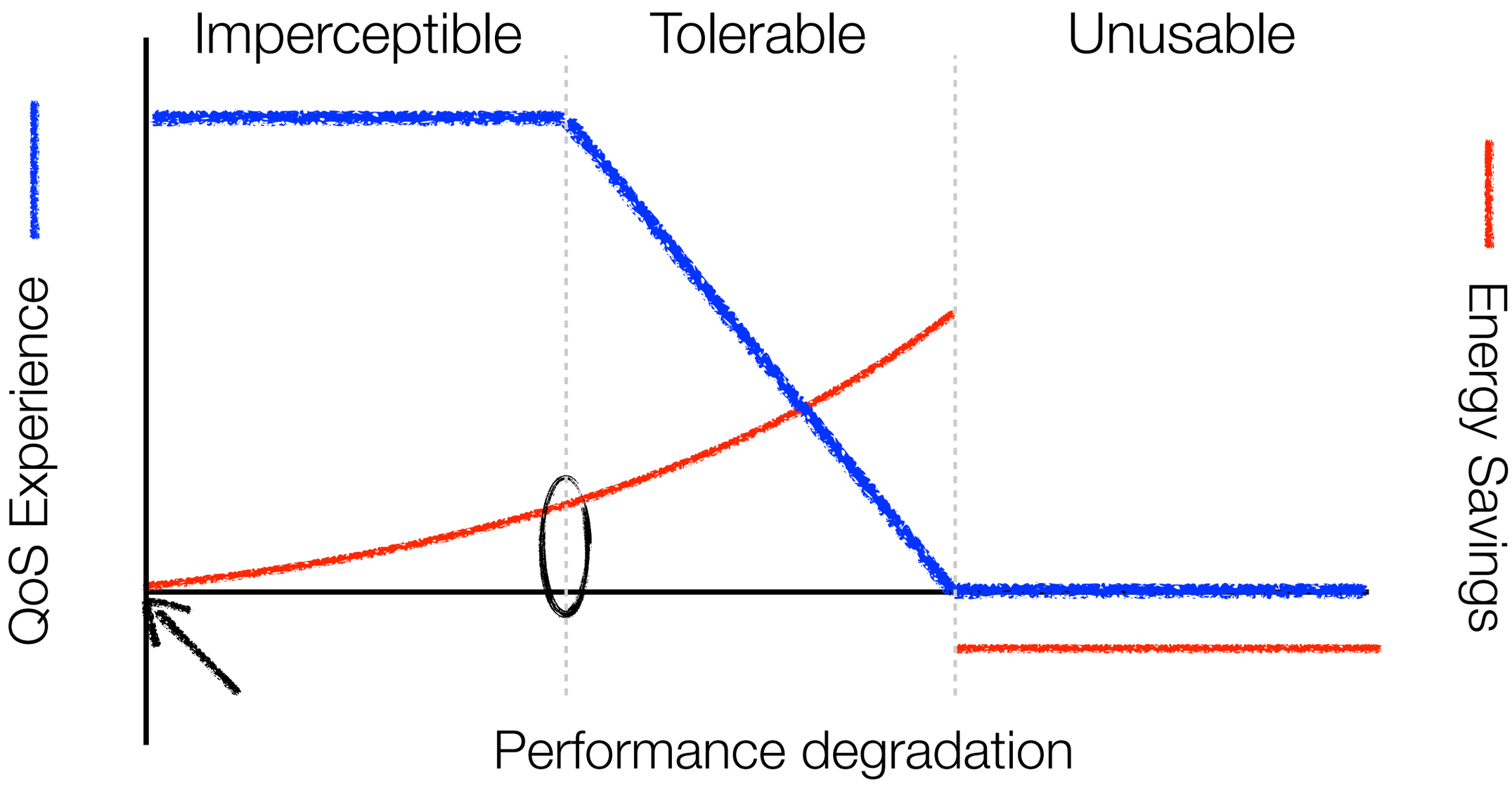


eQoS: Making a Calculated Trade-off



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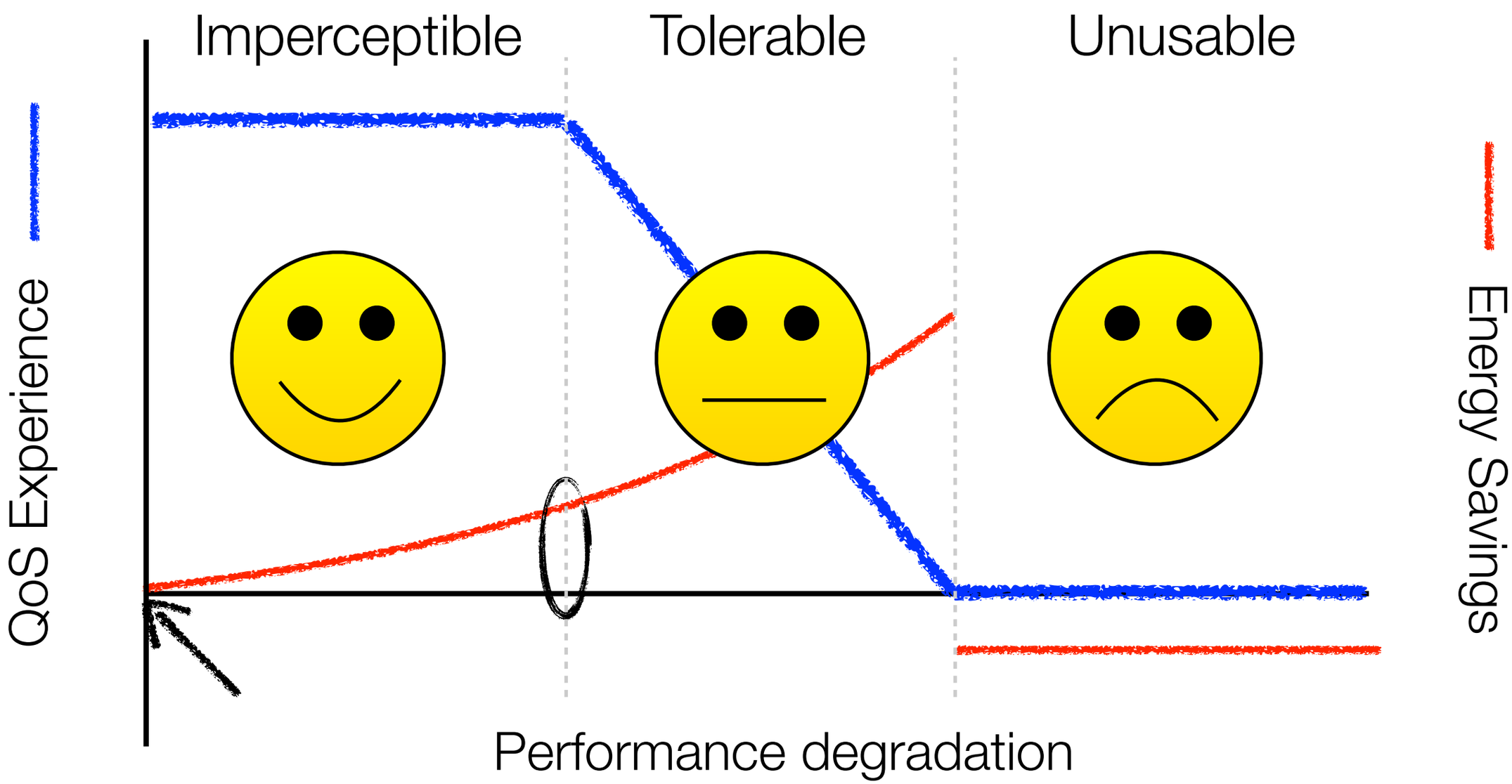

Interacting with an App

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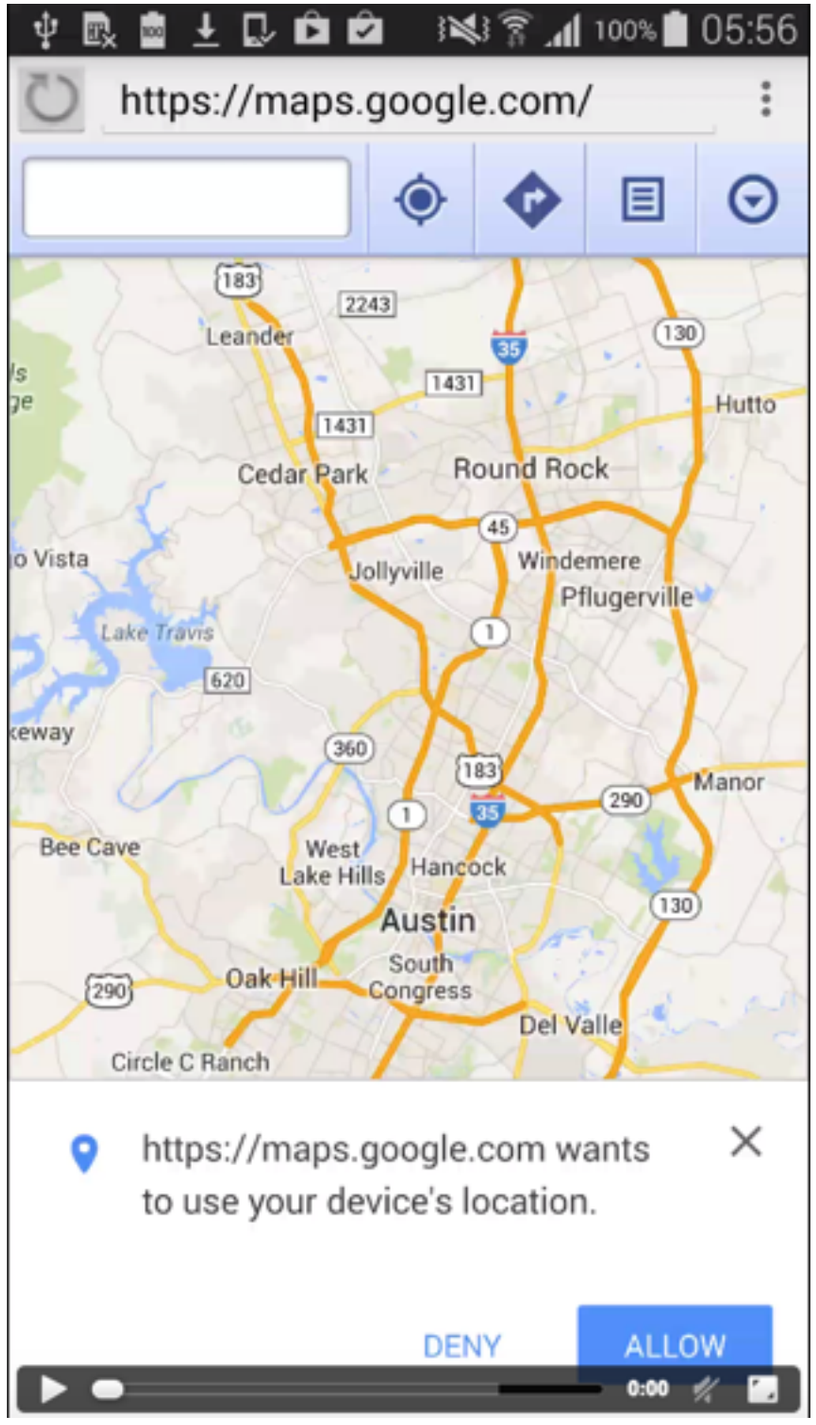

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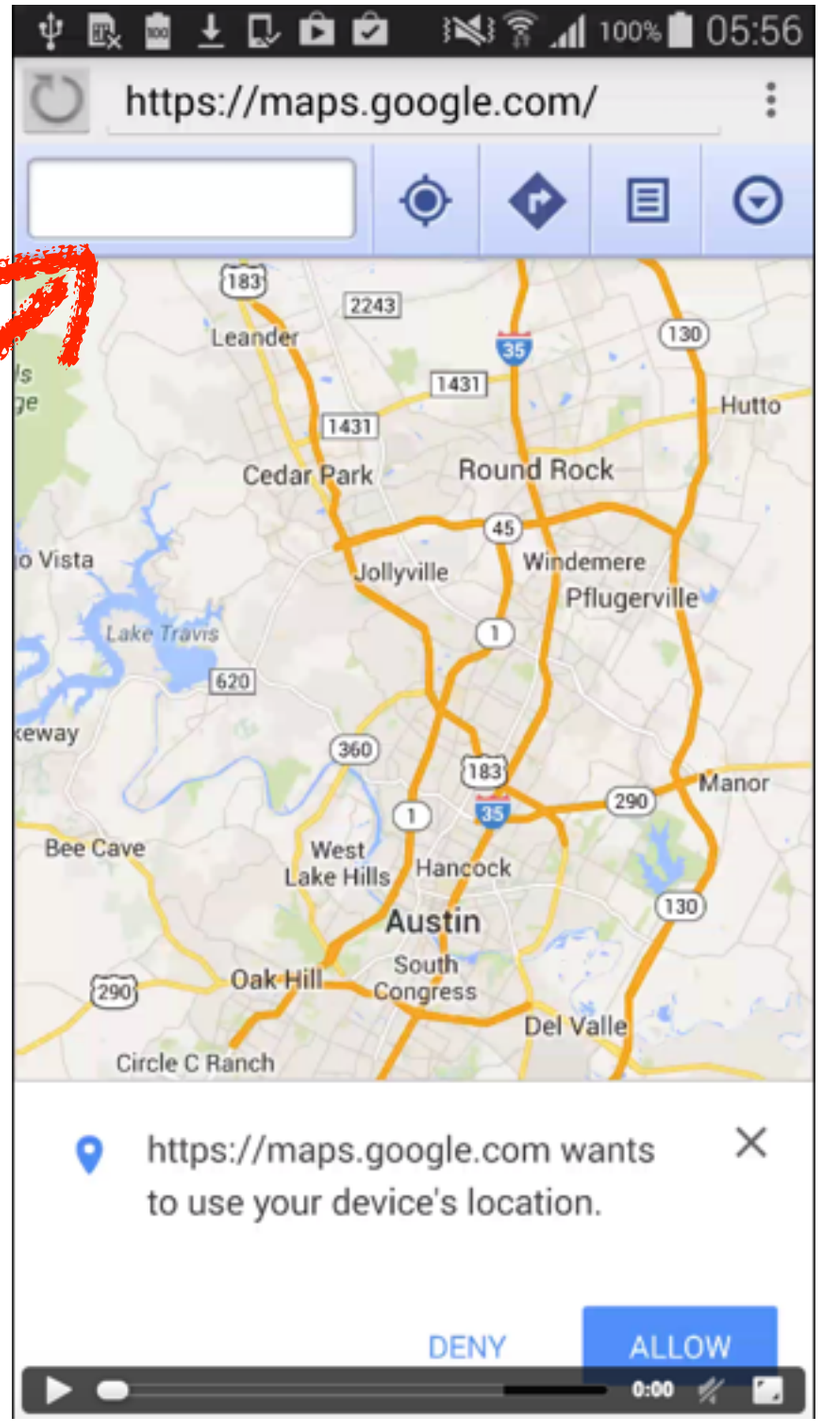

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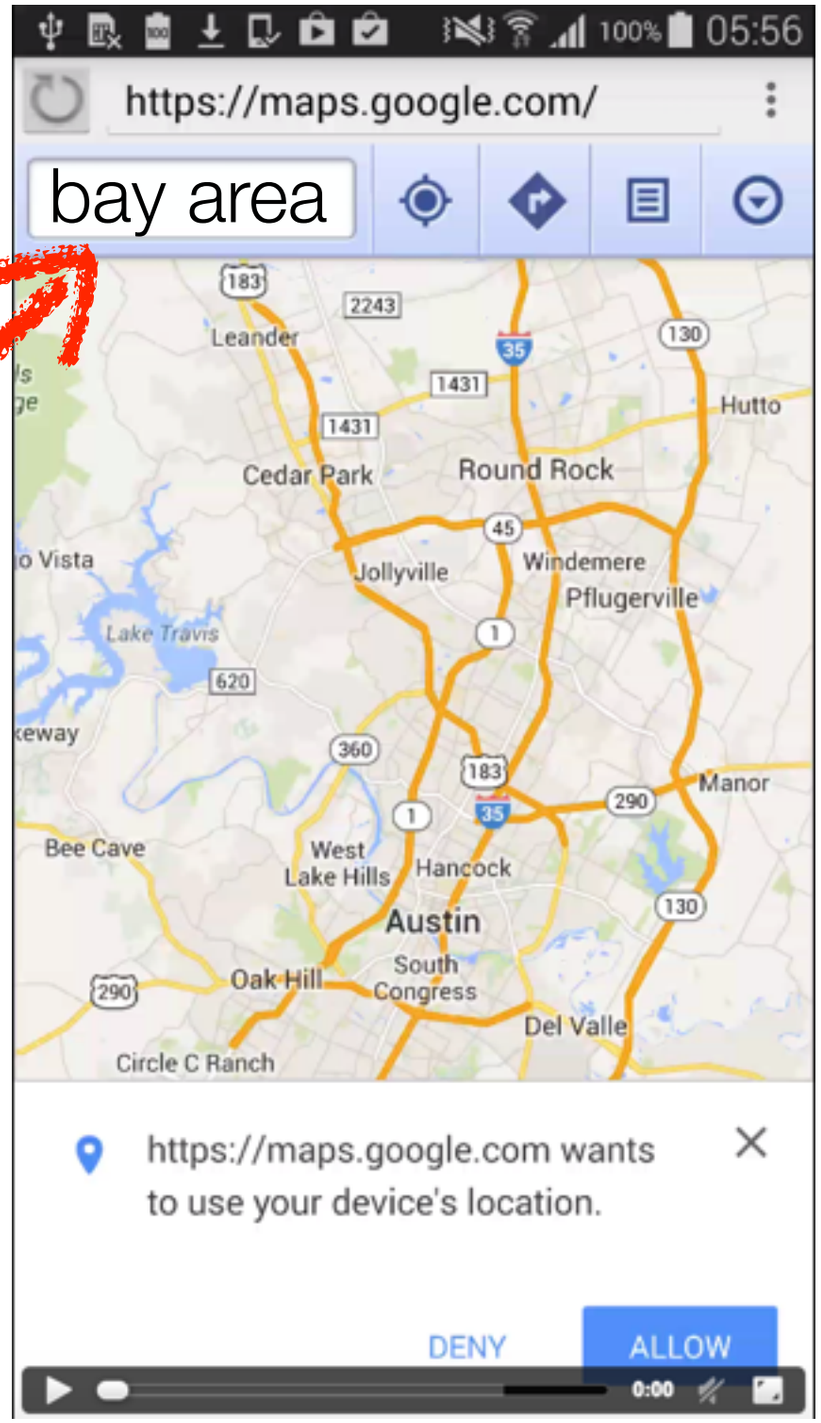

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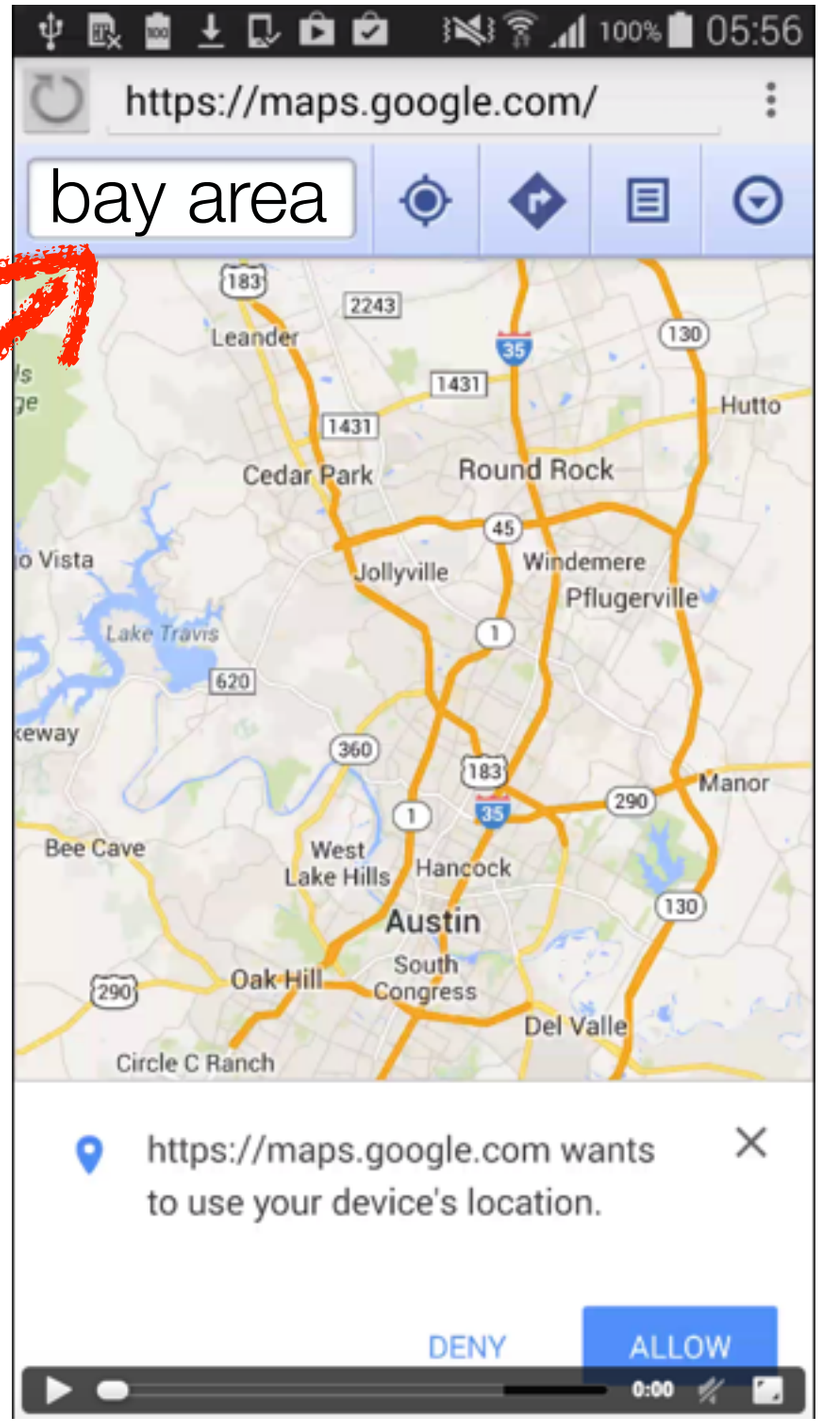

Interactions

typing

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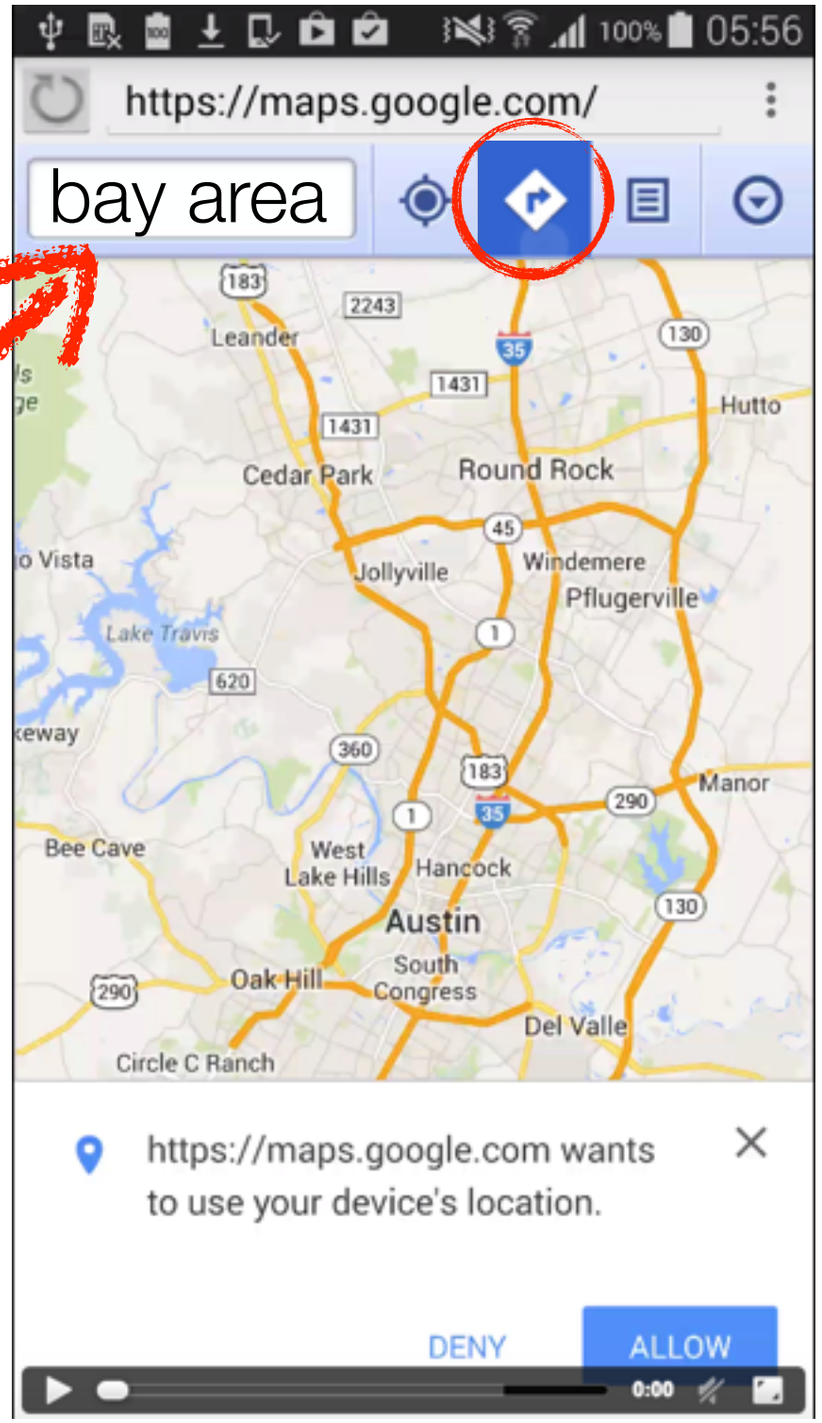

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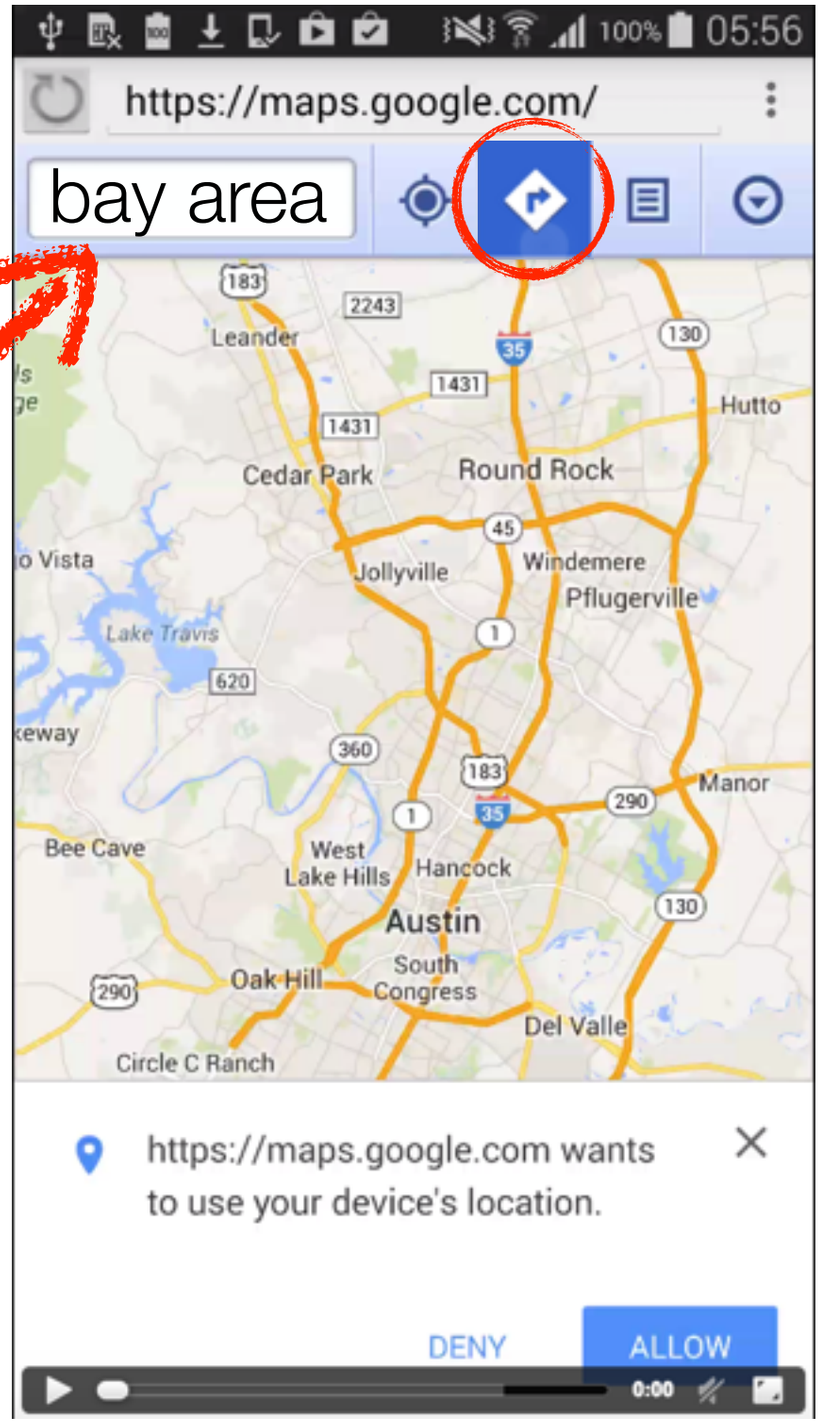

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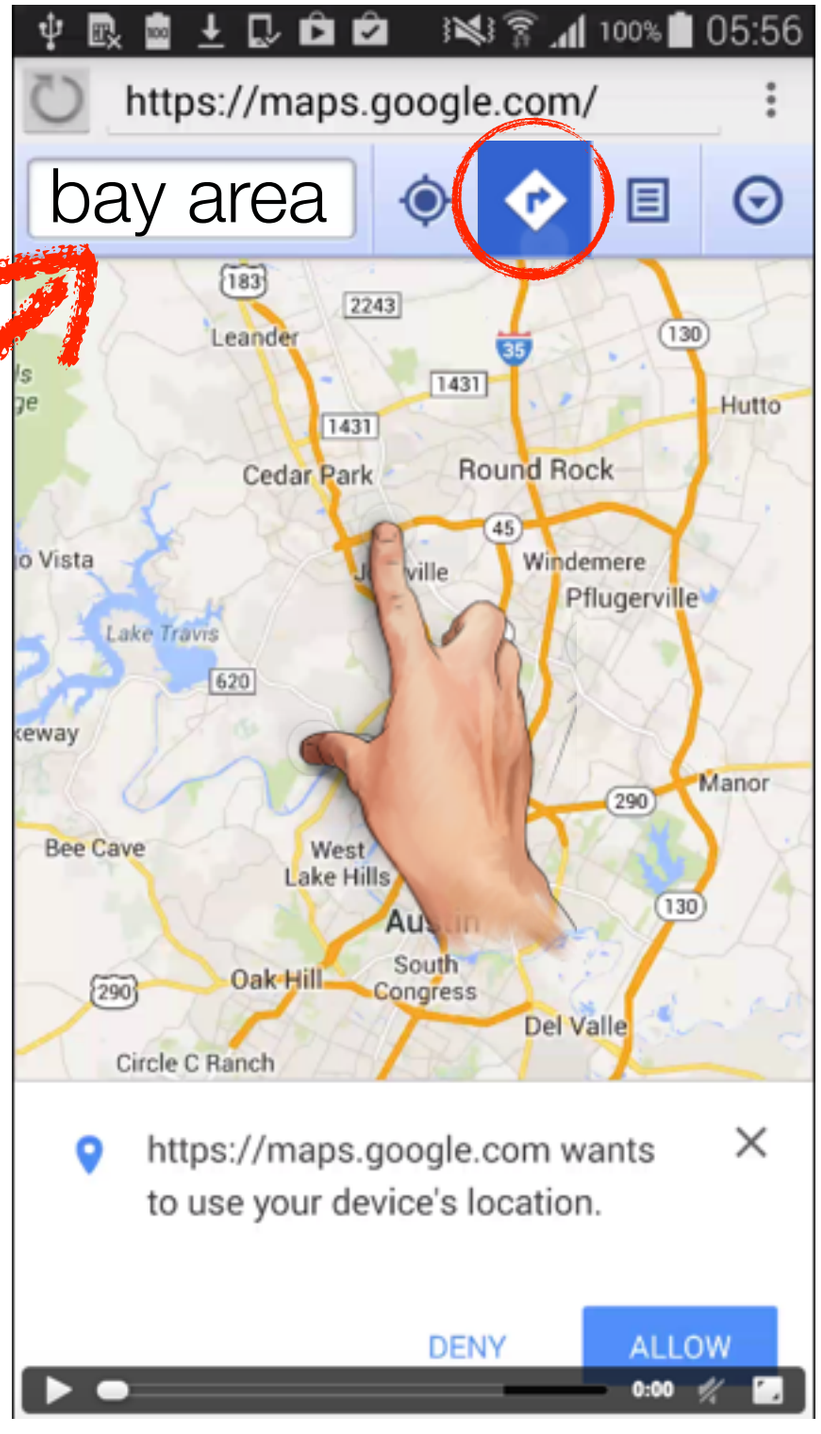

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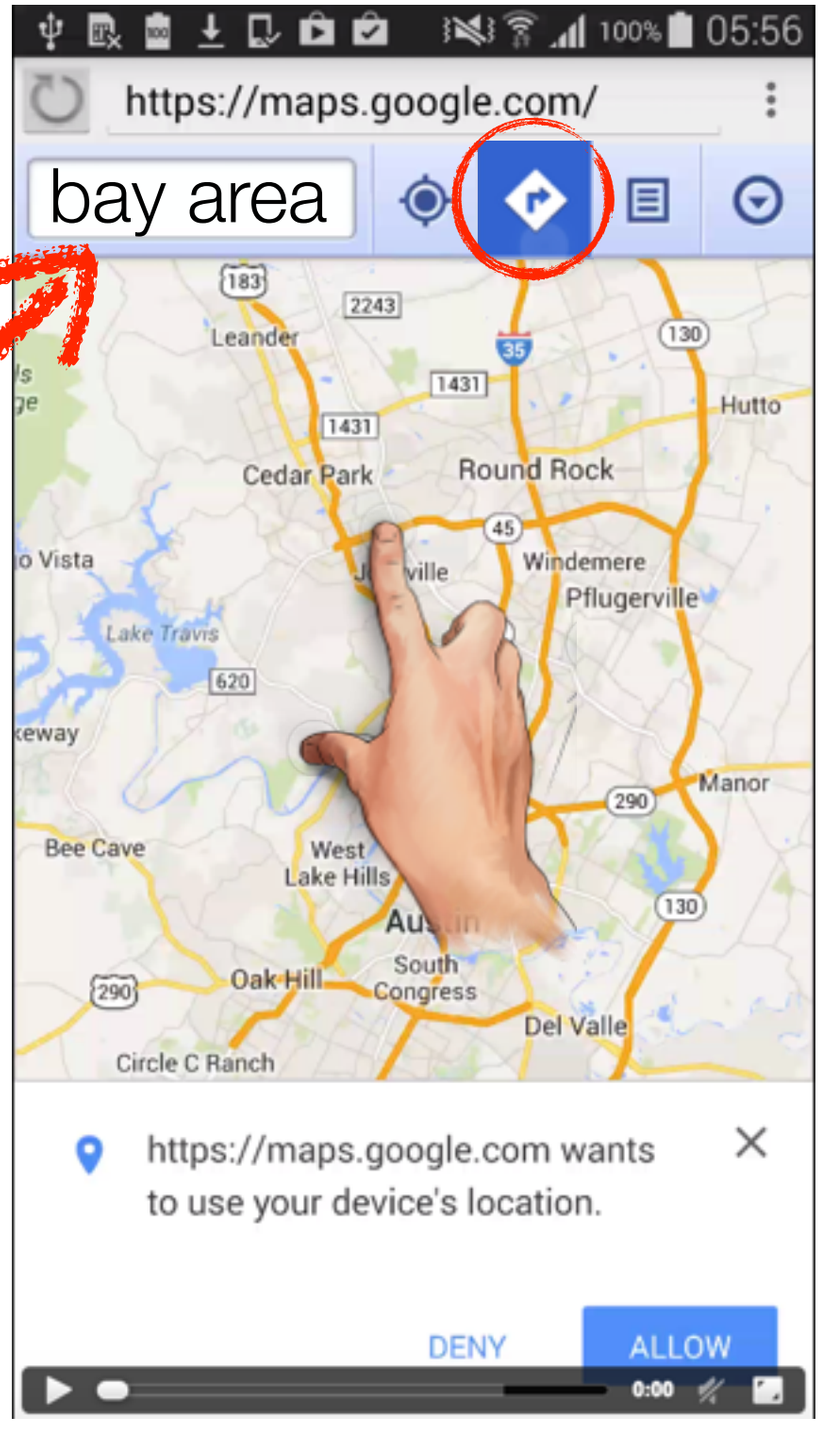

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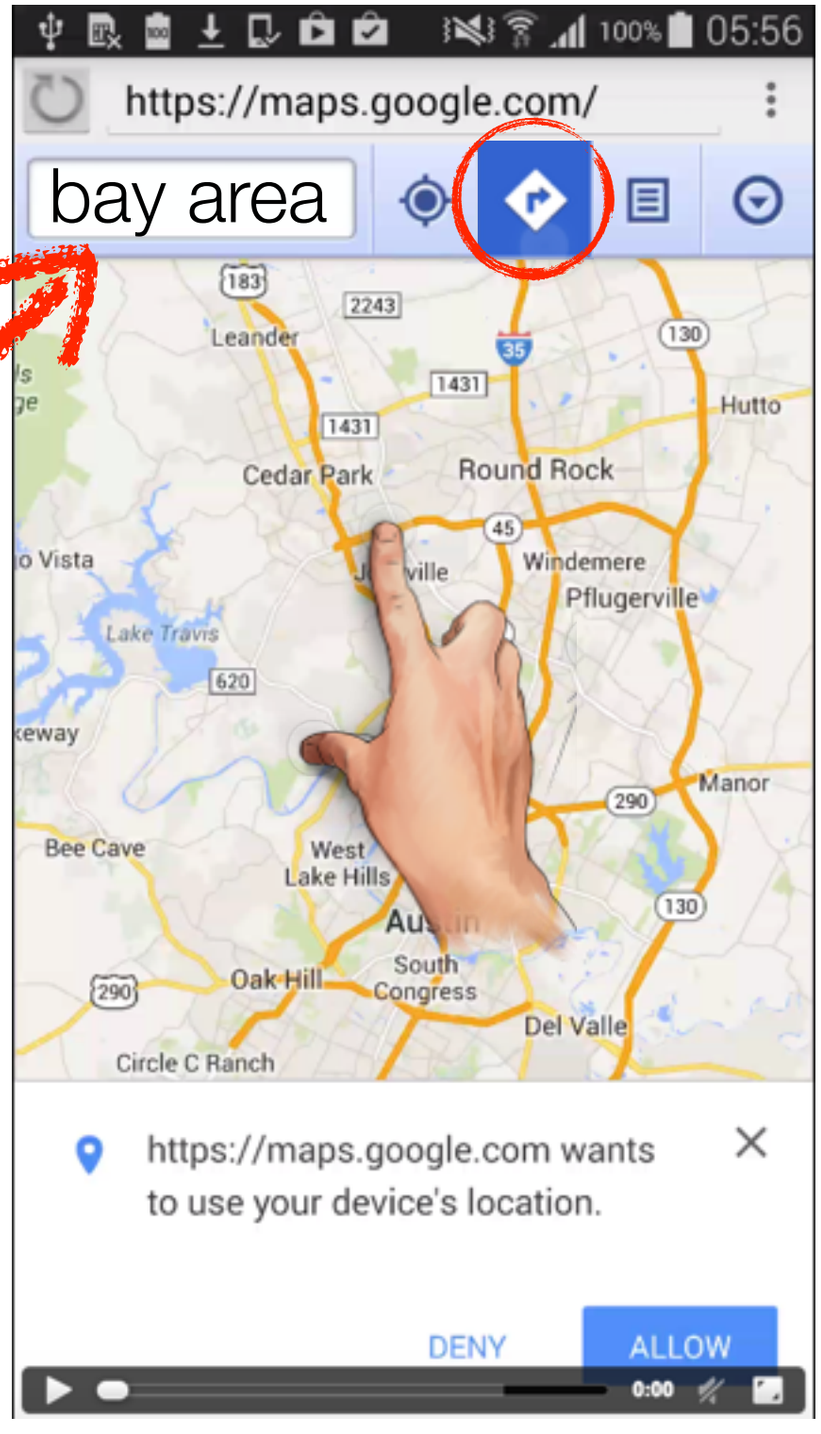

Interactions → Events

typing

pressing

moving

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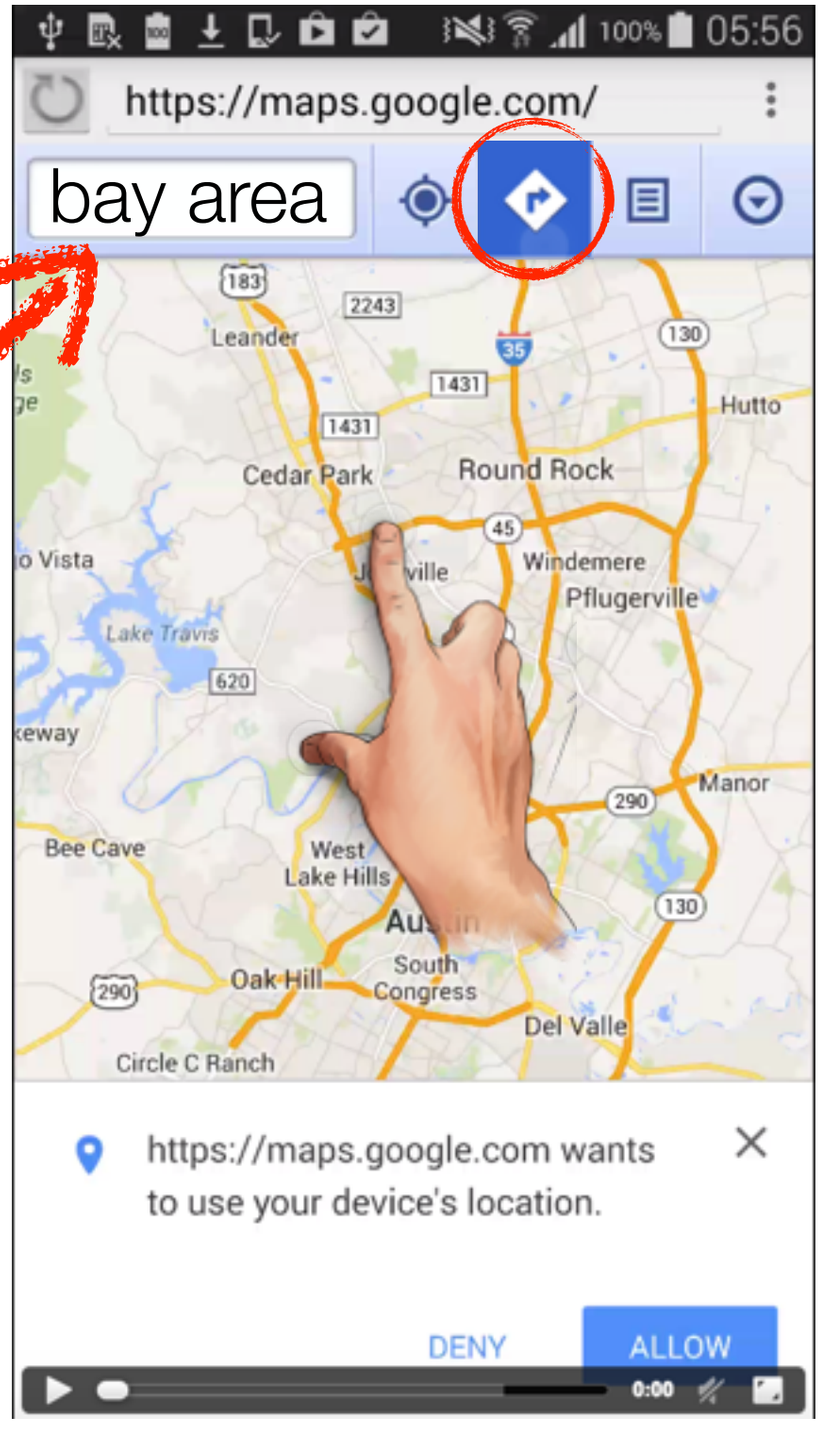

Interactions → Events

typing → `keypress`

pressing → `click`

moving → `touchmove`

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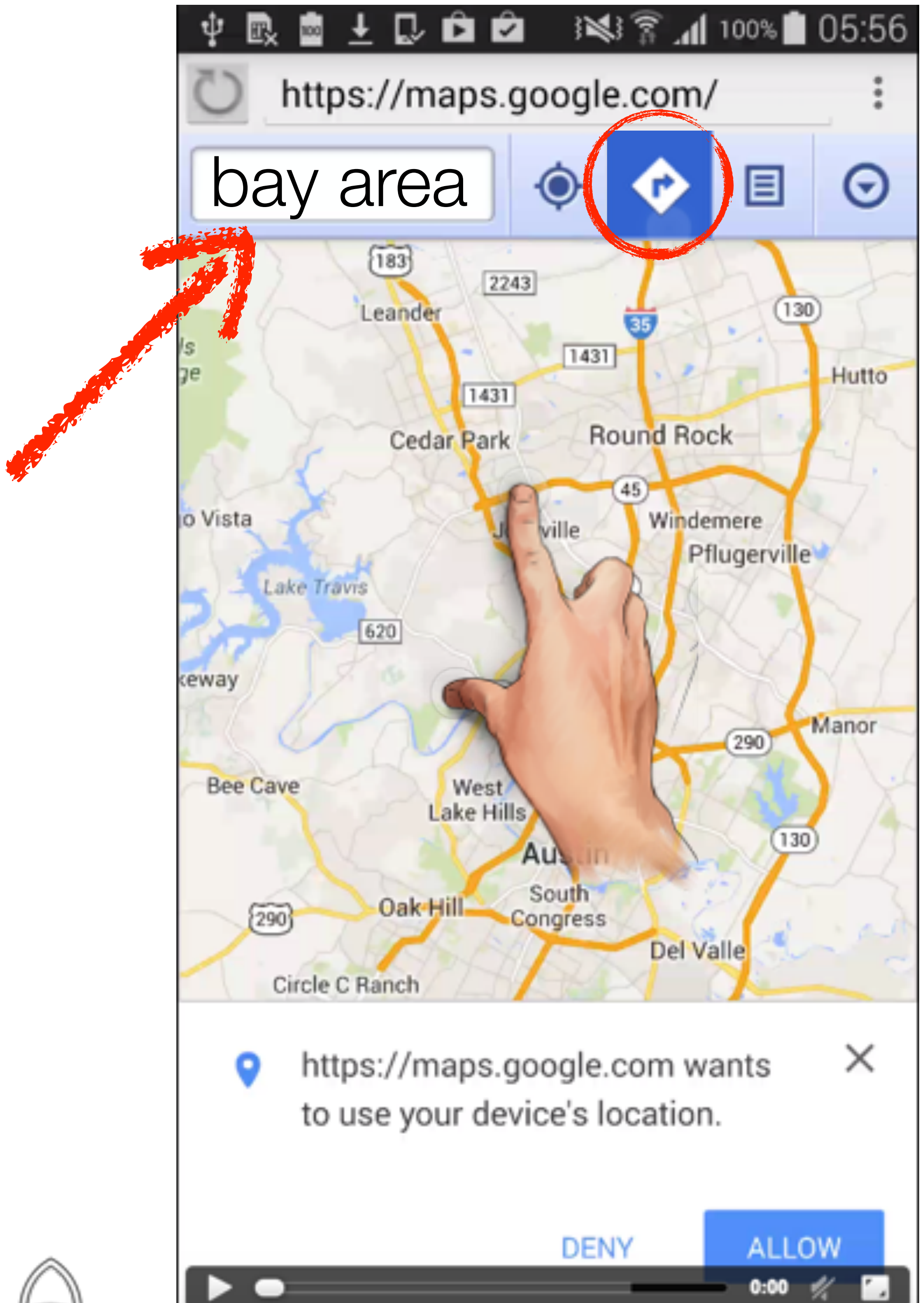
Interacting with an App



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selectstart @ DIV (1, 0)
mouseup @ DIV (1, 0)
DOMActivate @ DIV (1, 0)
DOMActivate @ DIV (1, 0)
click @ DIV (1, 0)
selectionchange @ #document (0, 0)
load @ SCRIPT (3, 59)
error @ IMG (0, 0)
error @ IMG (0, 0)
load @ SCRIPT (3, 59)
load @ SCRIPT (3, 59)
keydown @ INPUT (16, 1)
webkitBeforeTextInserted @ DIV (1, 0)
webkitEditableContentChanged @ DIV (1, 0)
input @ DIV (1, 0)
textInput @ INPUT (16, 1)
keypress @ INPUT (16, 1)
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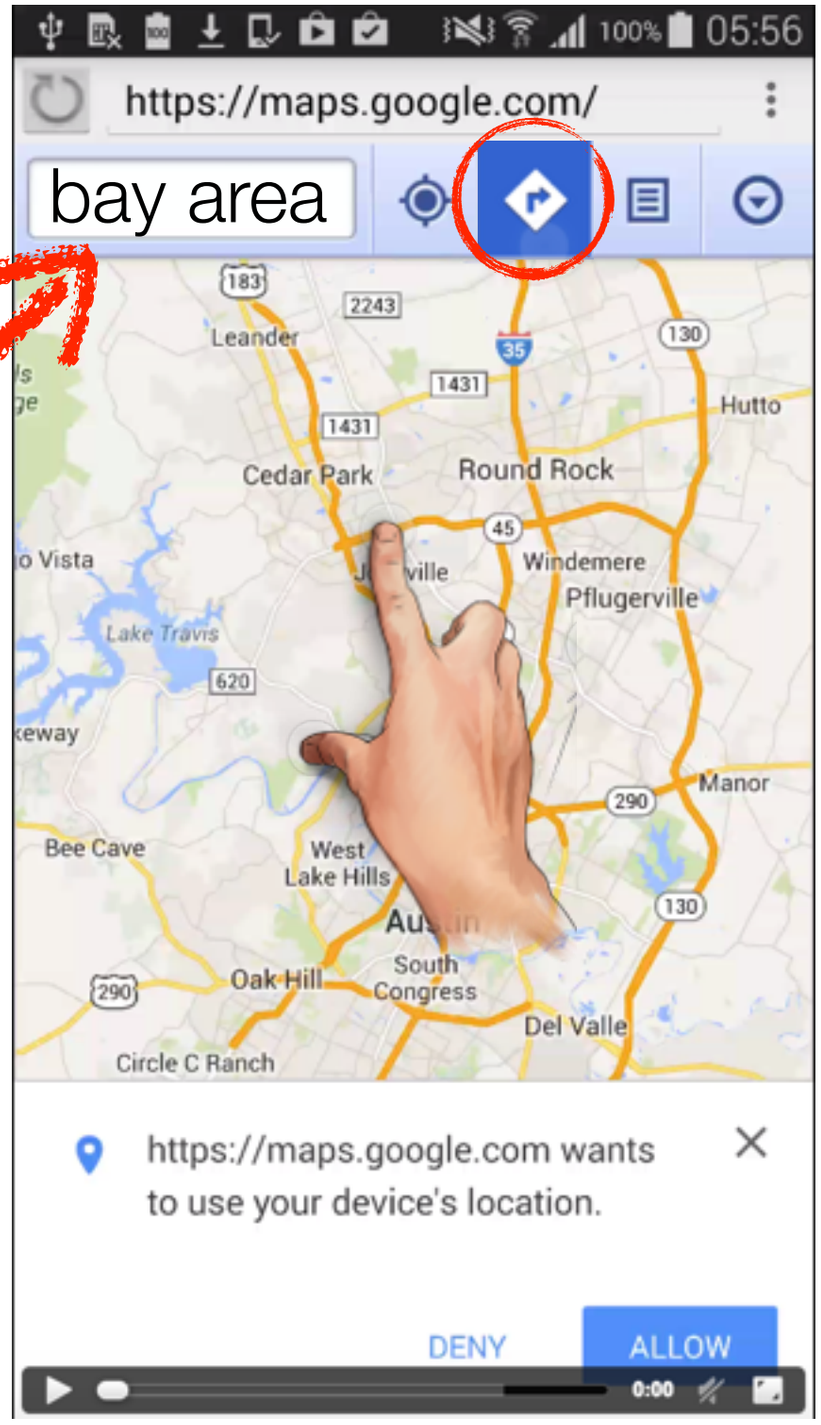

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1487 Events

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Mobile Web Applications are Event-Driven

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Event FIFO Queue

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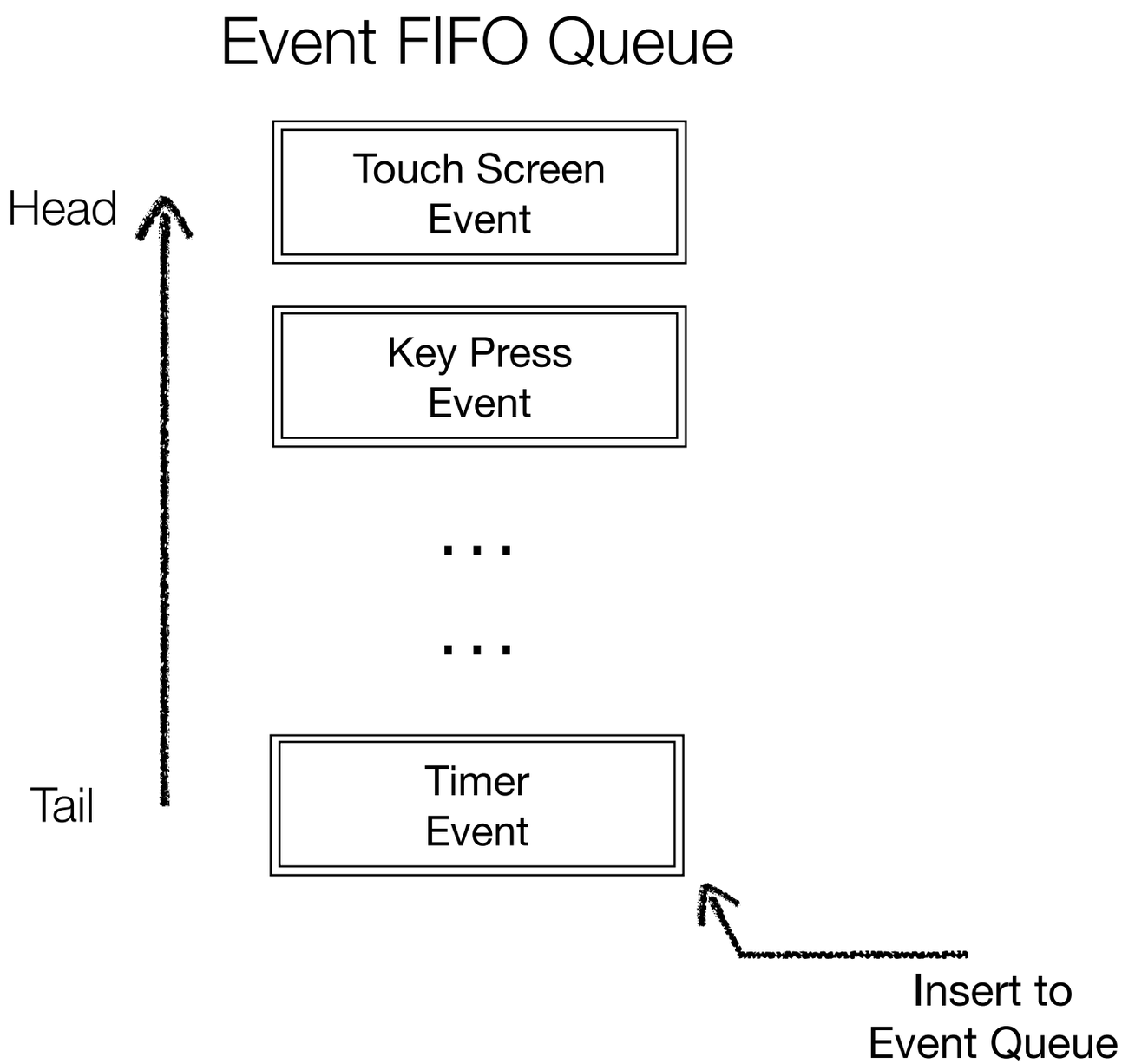

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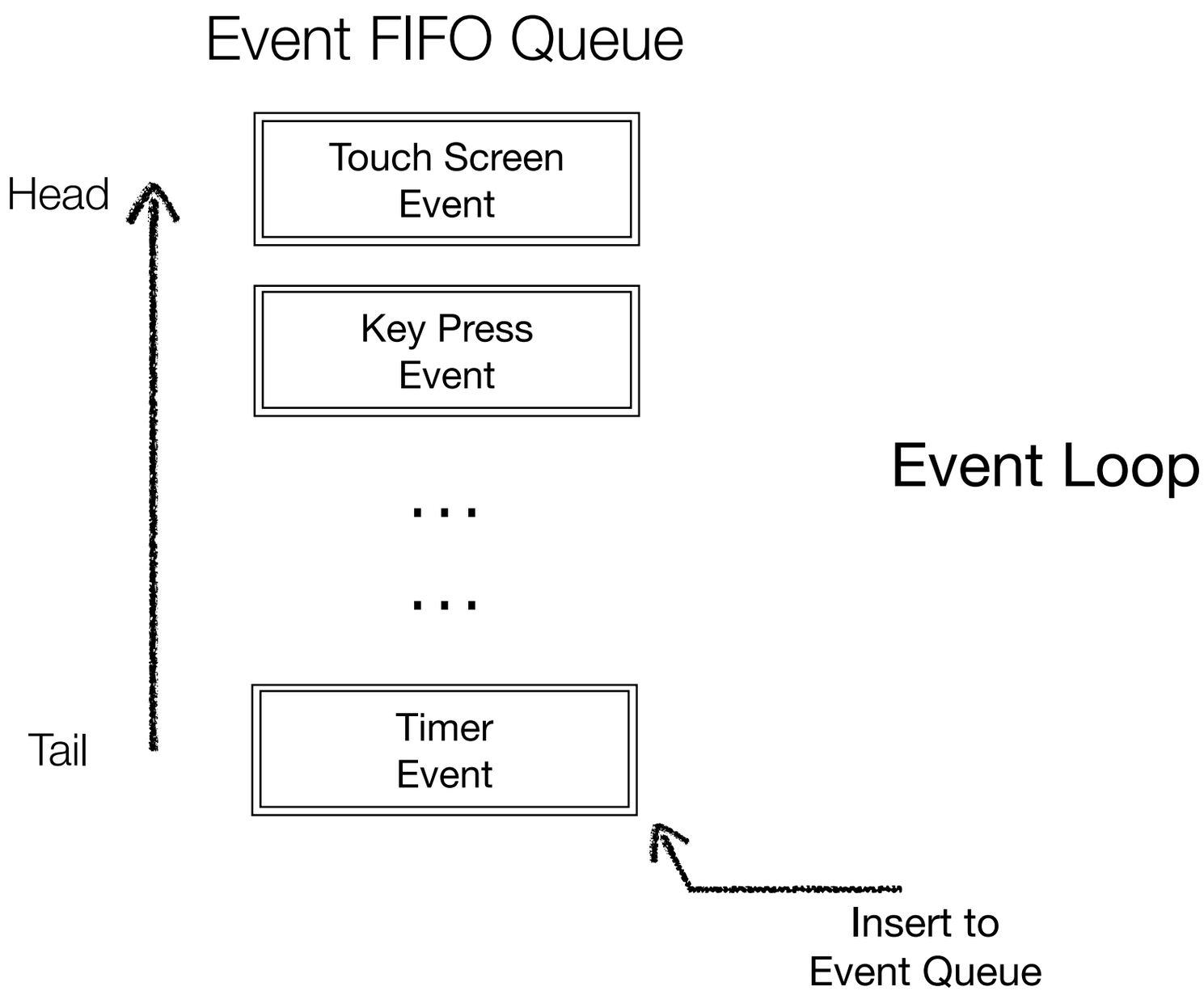

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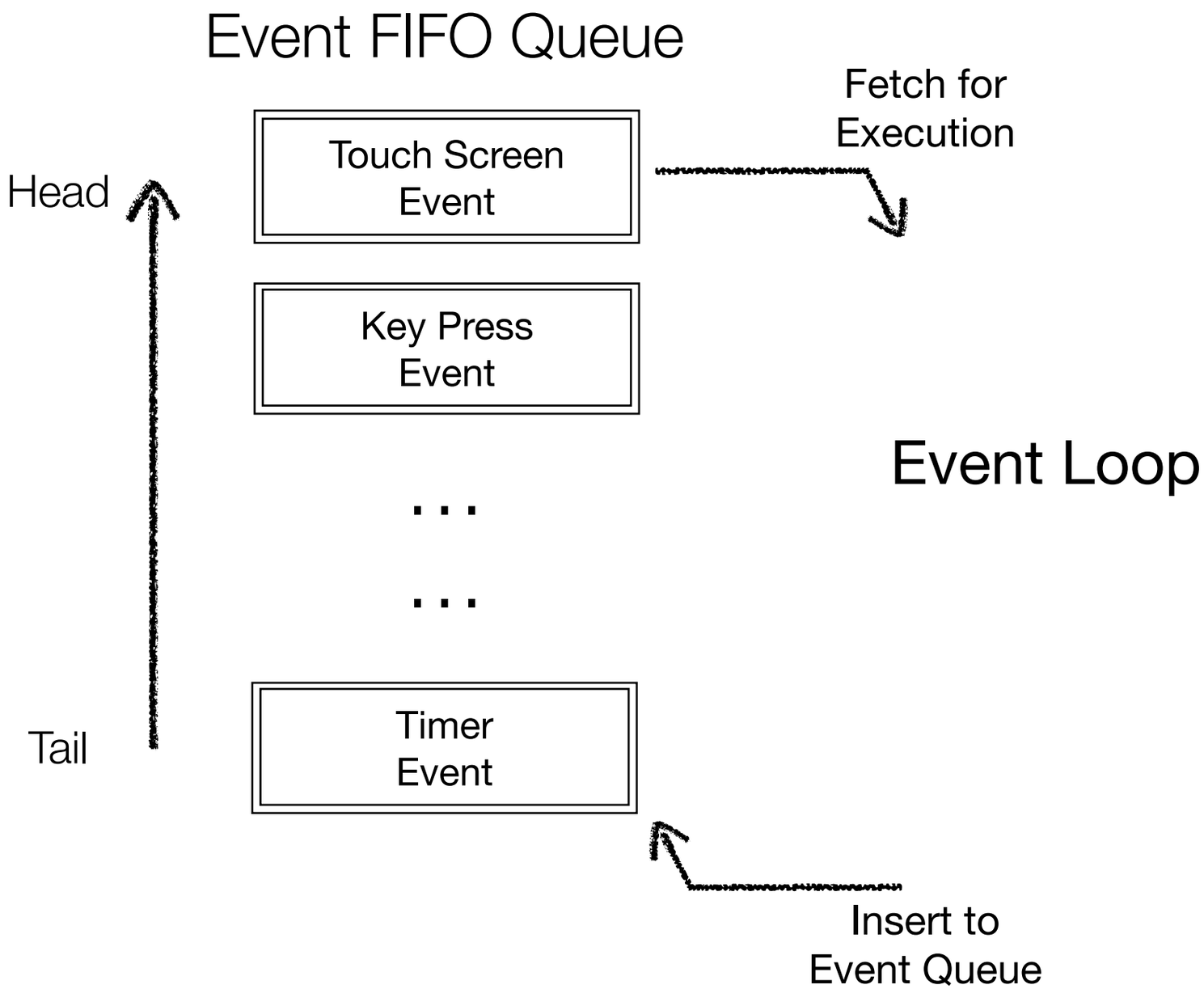

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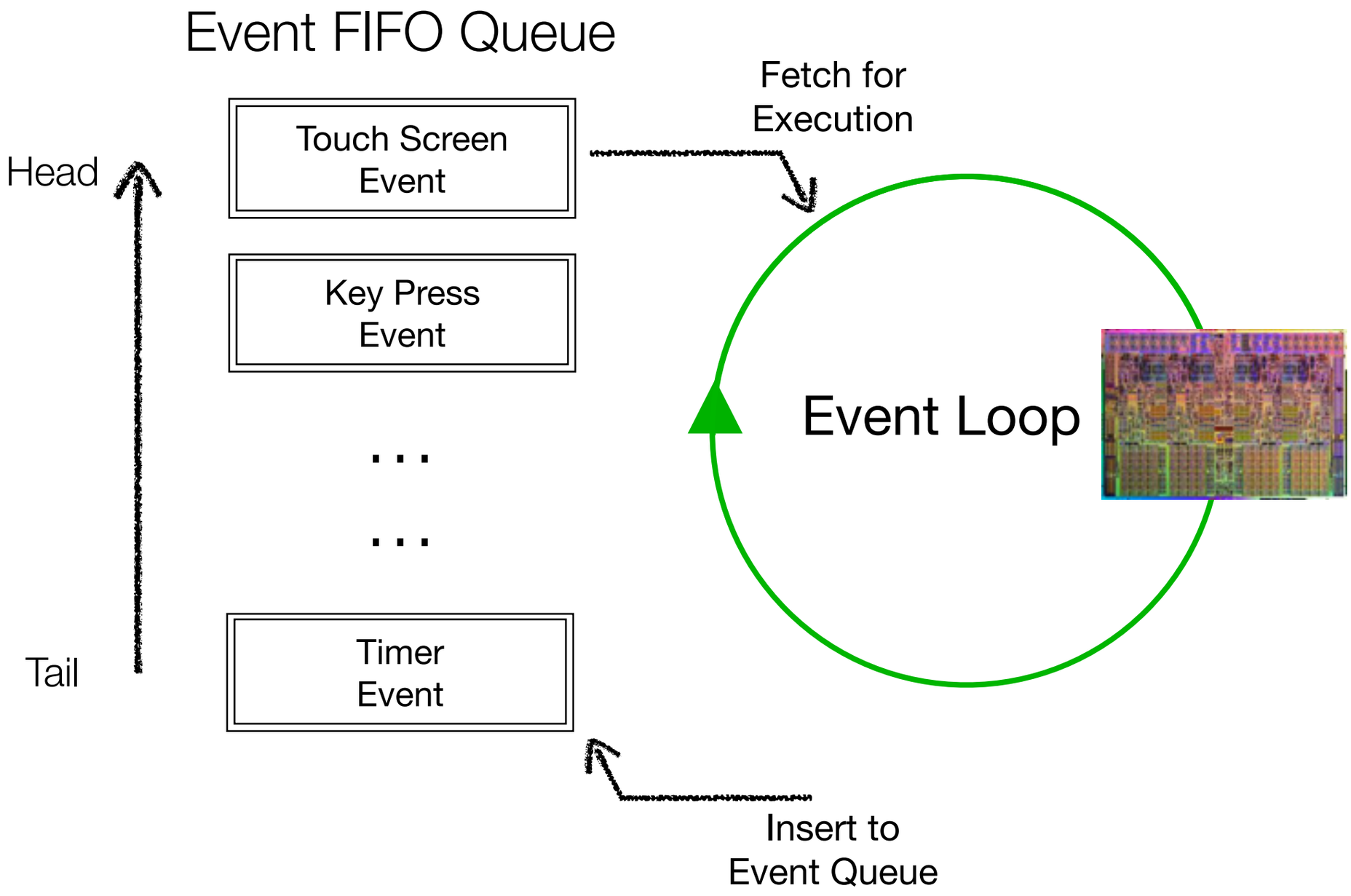

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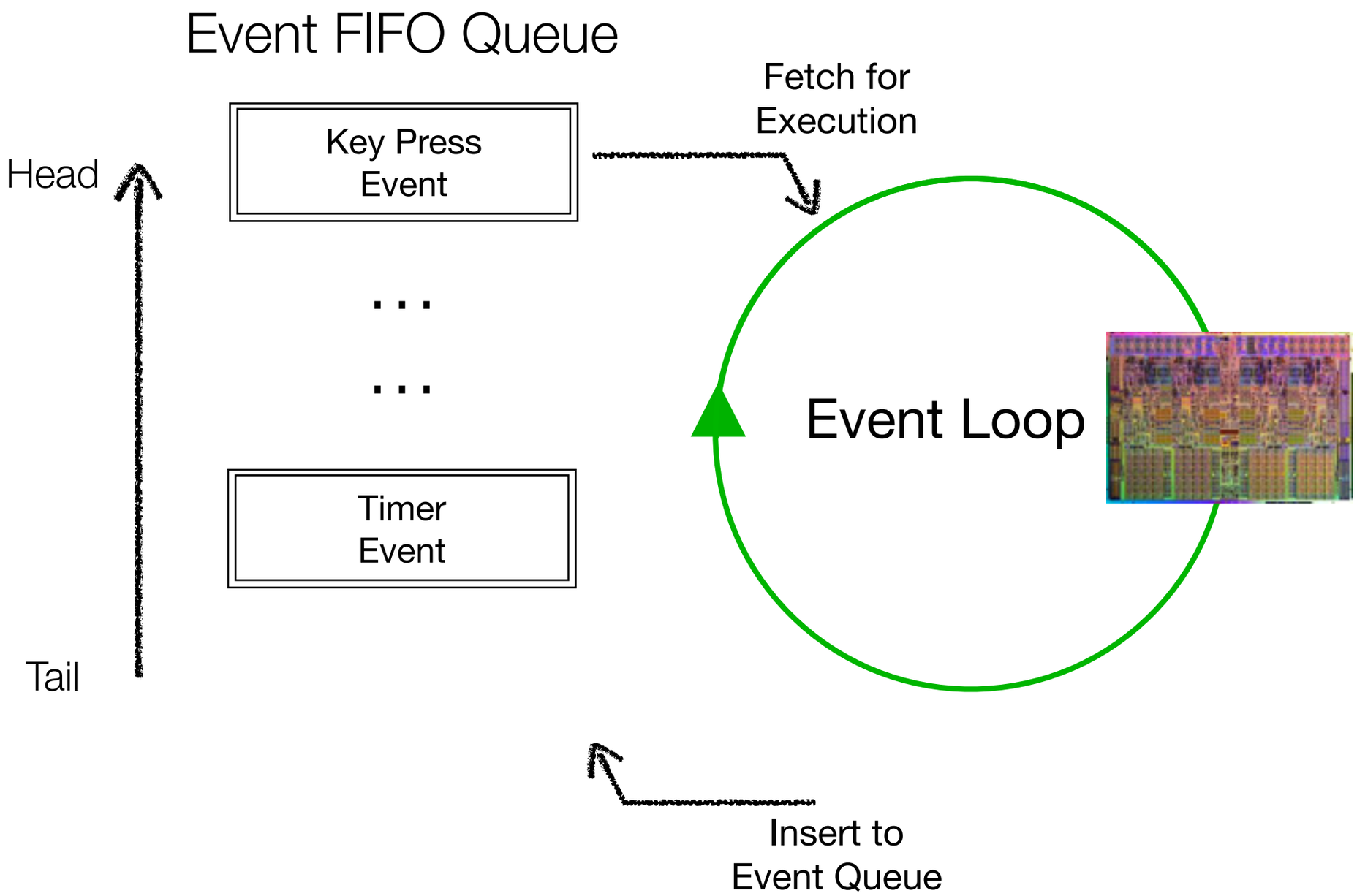

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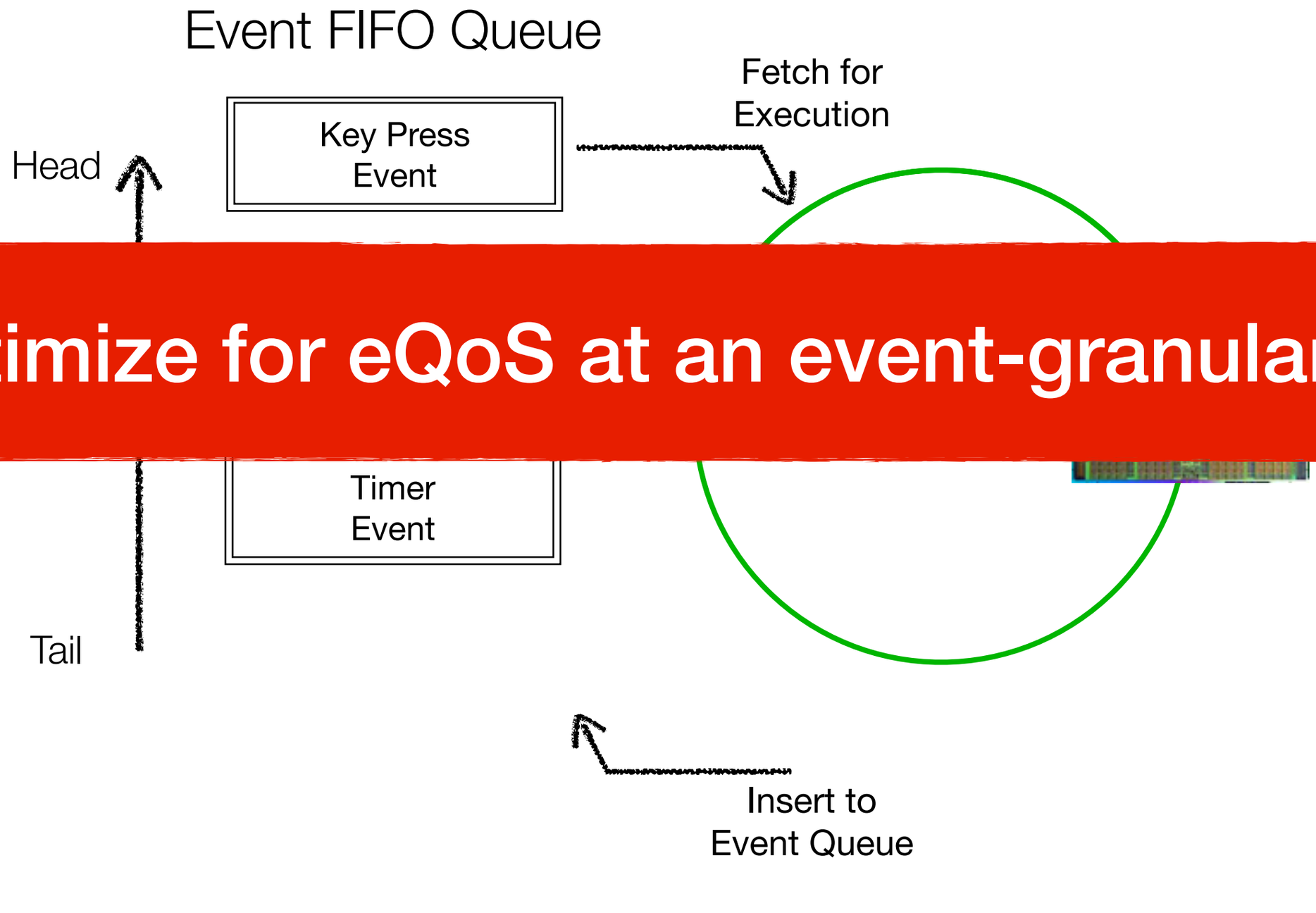

Optimize for eQoS at an event-granularity

Executive Summary

- **Key idea**: Execute **events** with just-enough energy to meet user QoS expectation
  - Develop a runtime system that leverages the large scheduling space of heterogeneous CPUs

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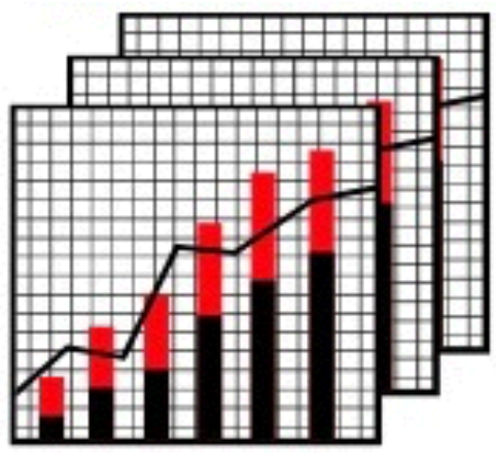

Event-level Characterization

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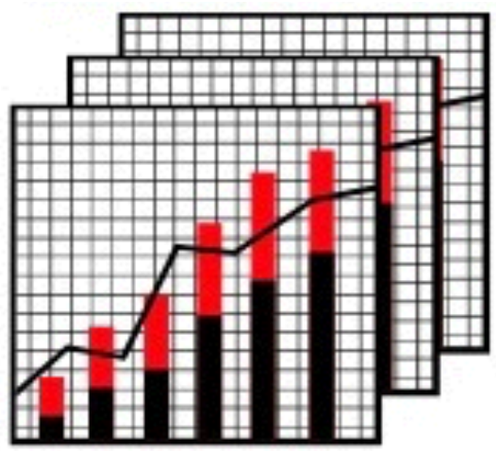

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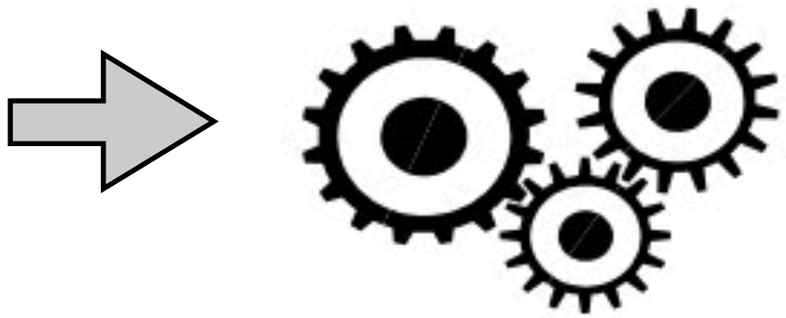

Runtime Mechanics to Exploit Latency Slack

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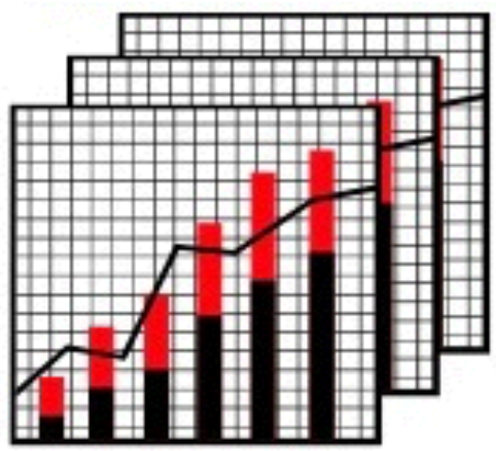

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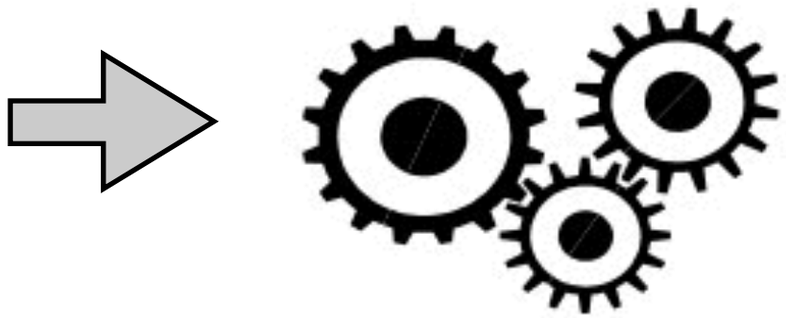

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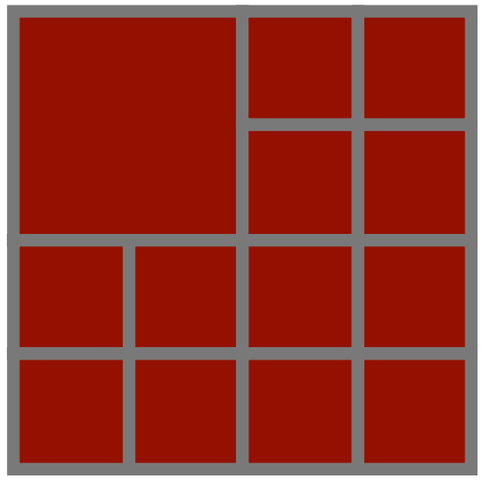

Heterogeneous Resource Utilization

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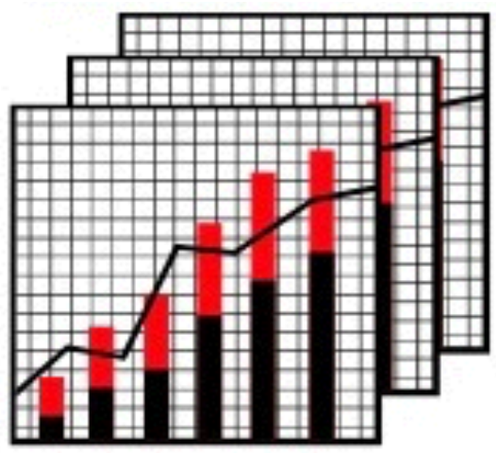

Event-level Characterization

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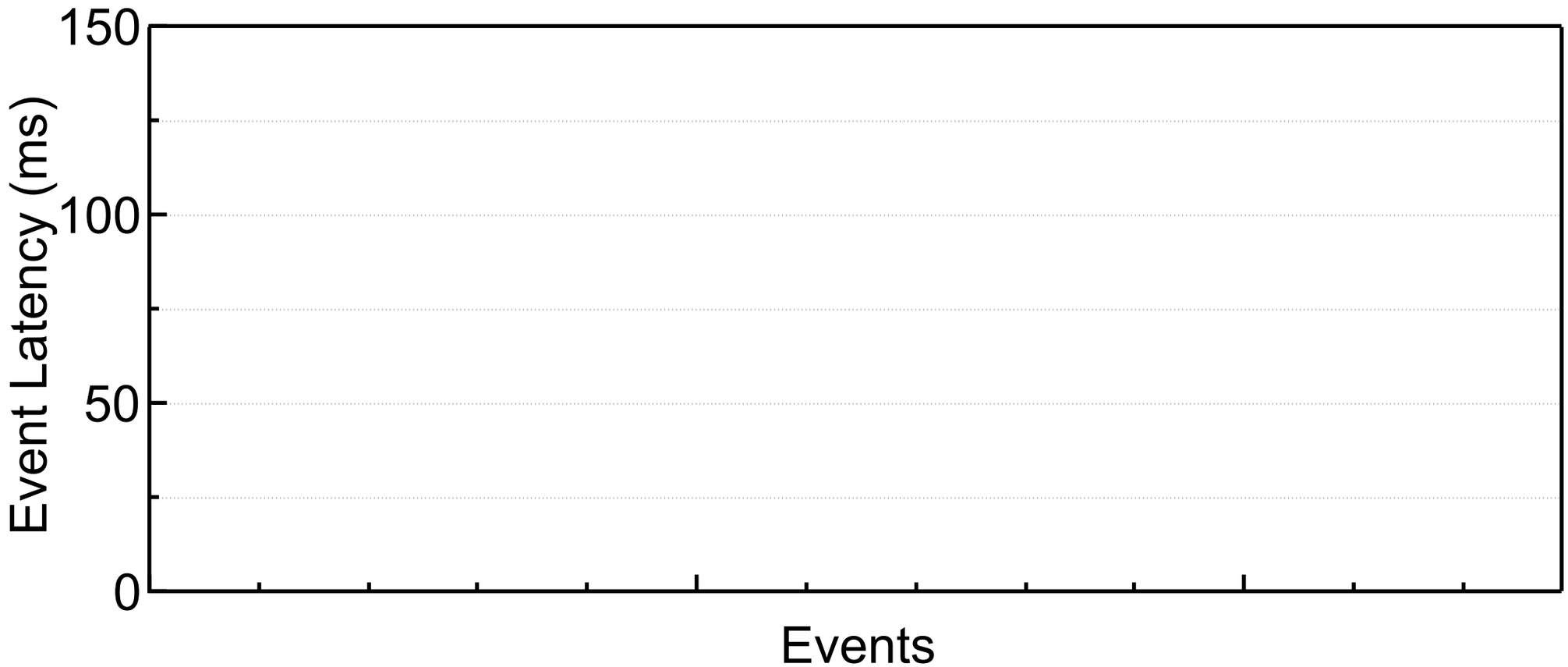
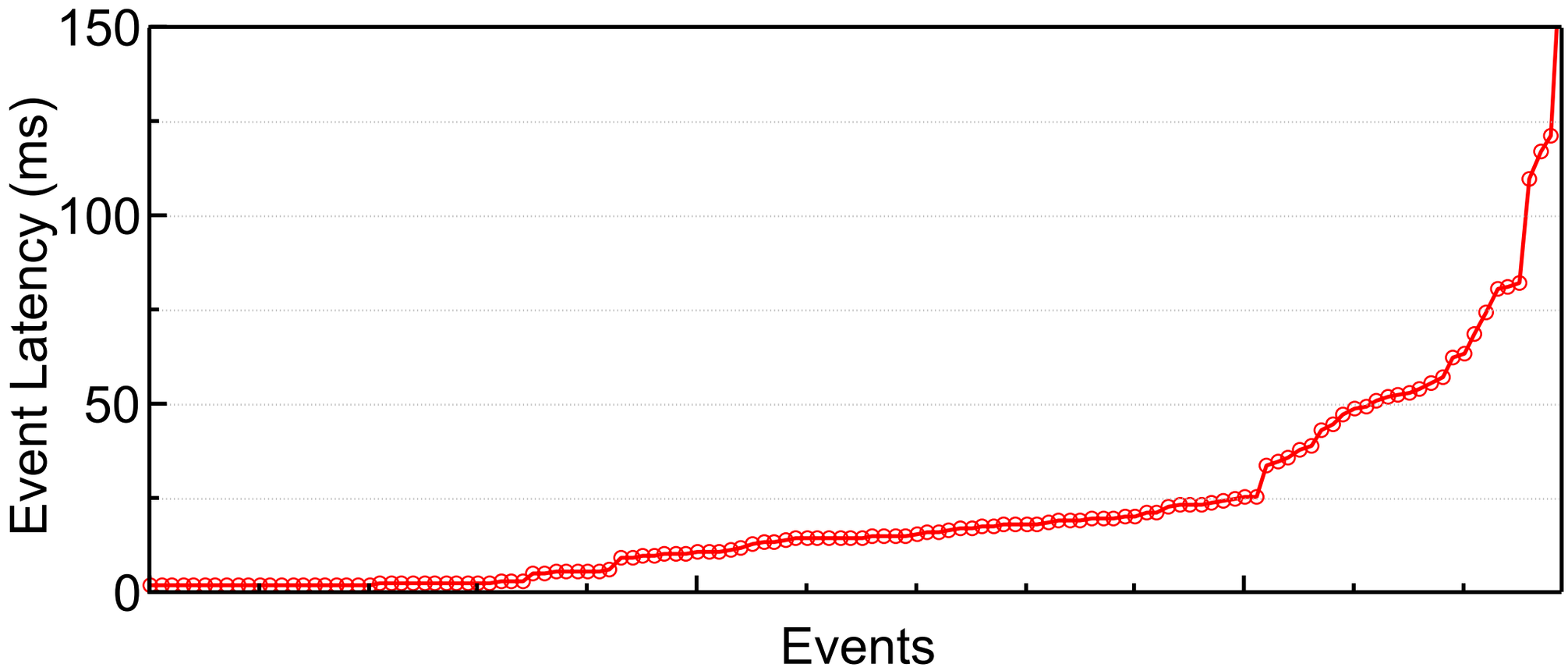
Heterogeneous Resource Utilization

Exploit the Slack in Events



Exploit the Slack in Events



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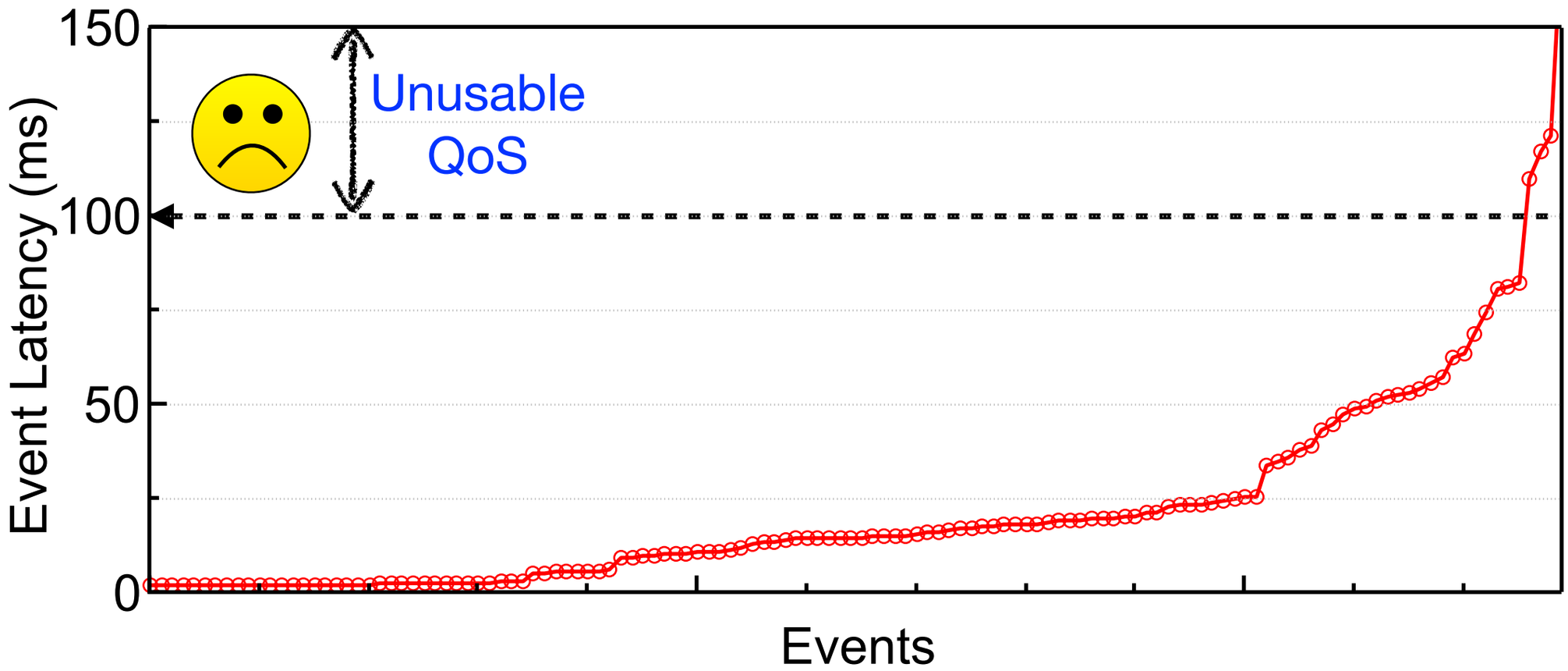

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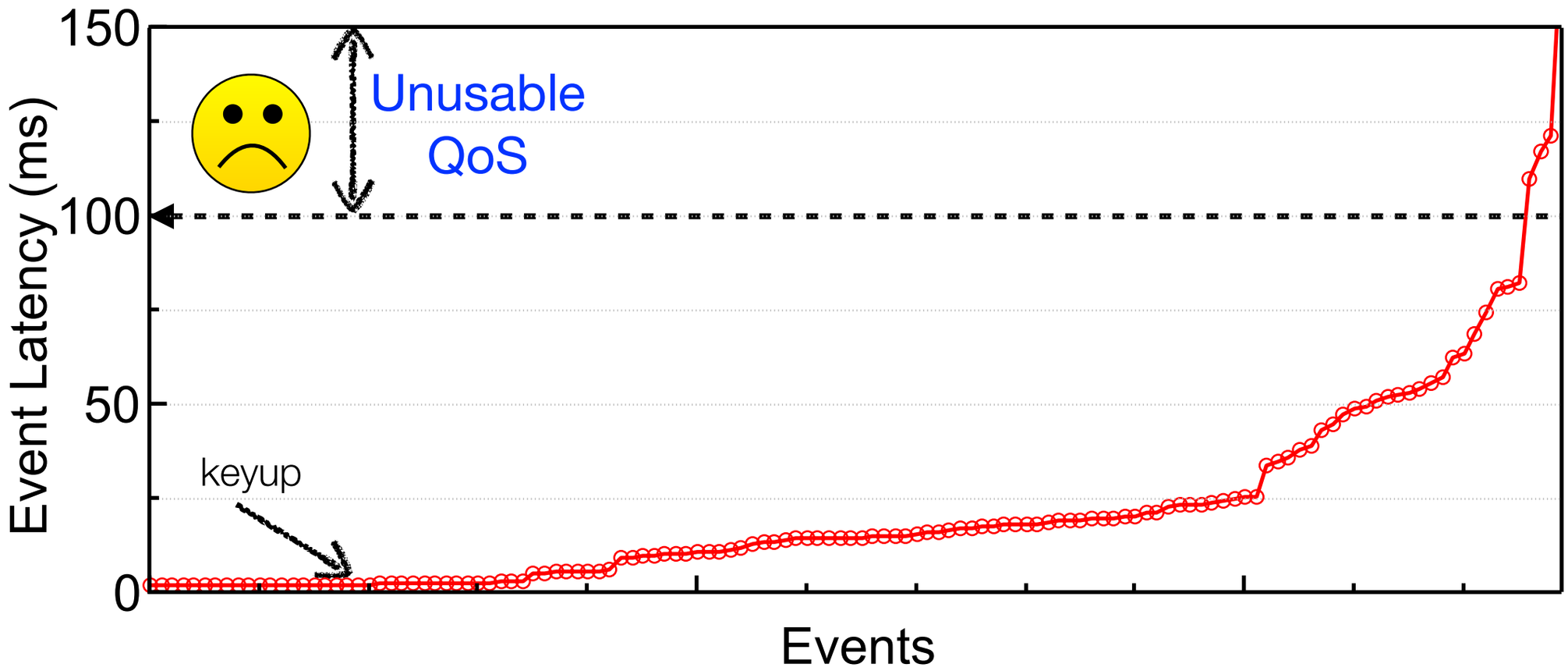

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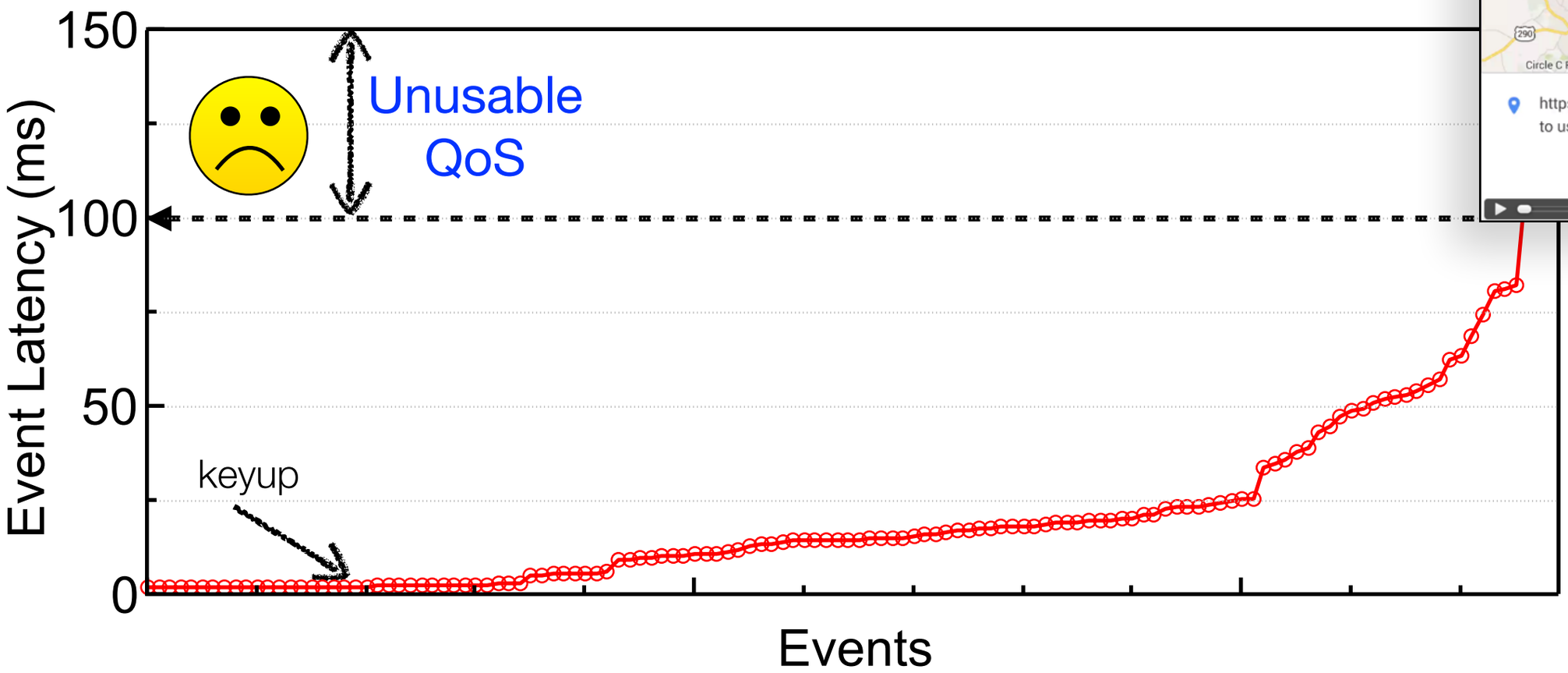

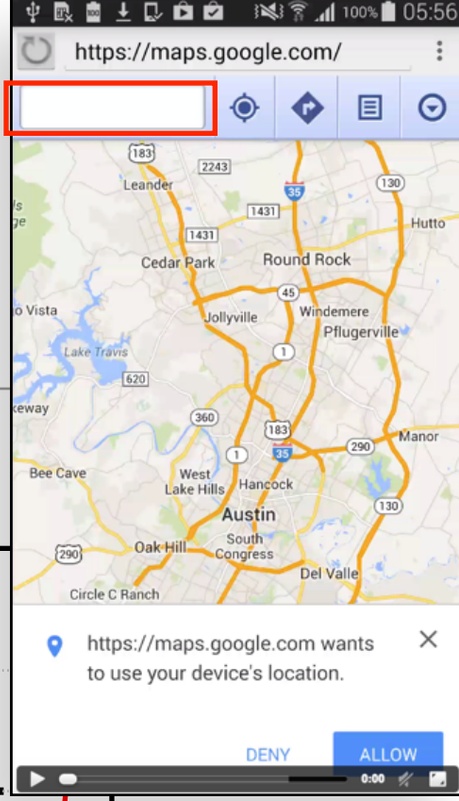

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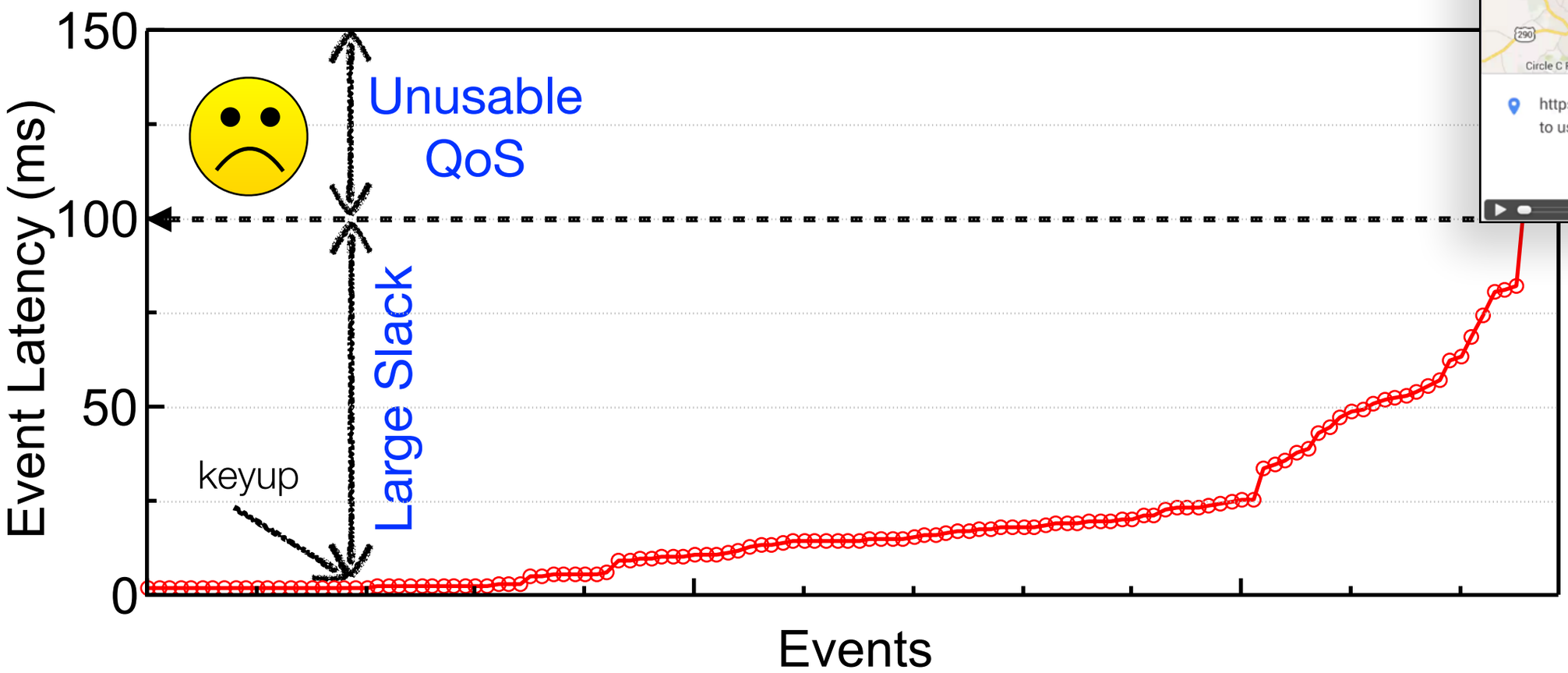

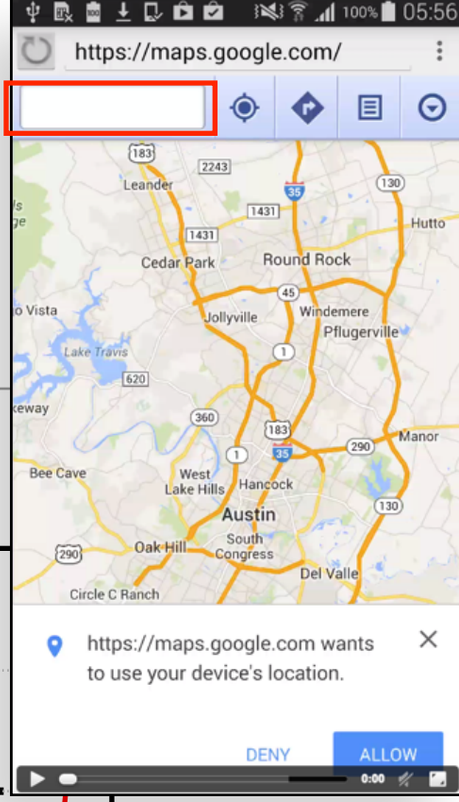

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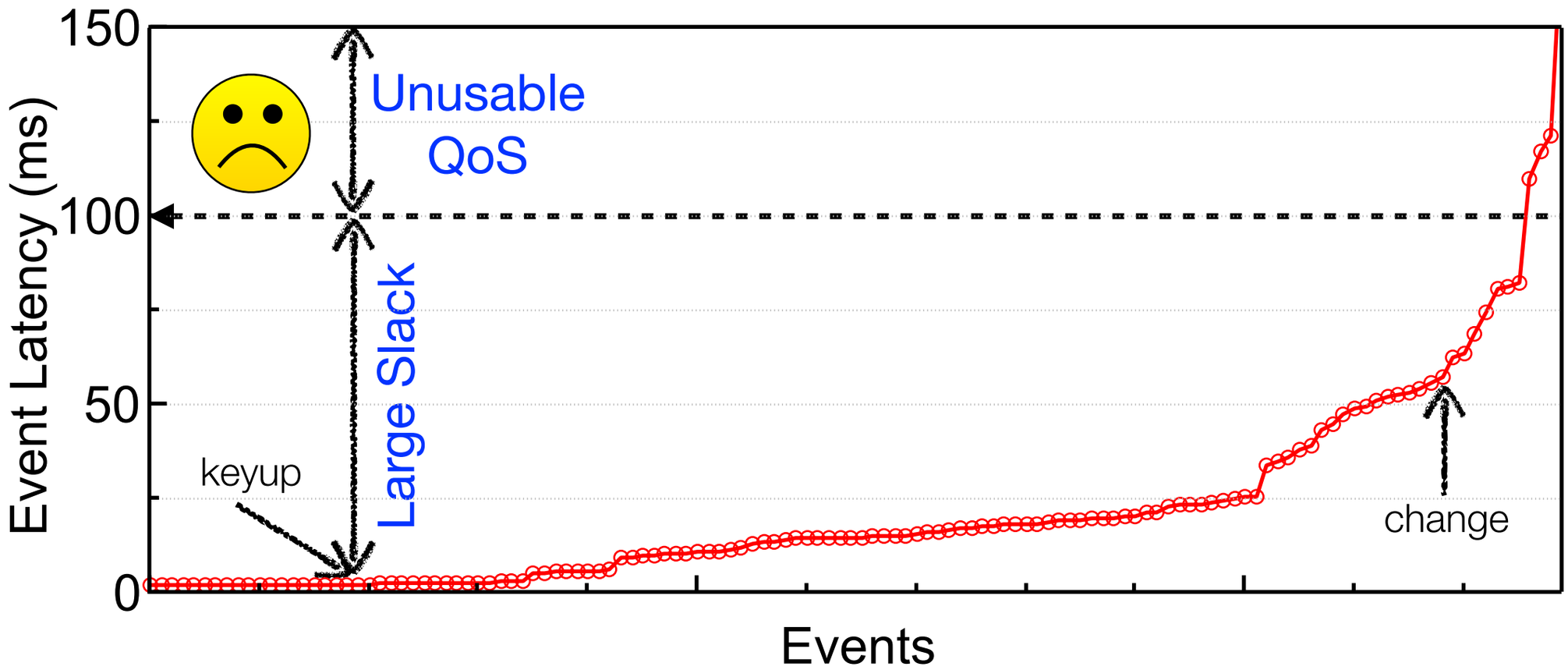

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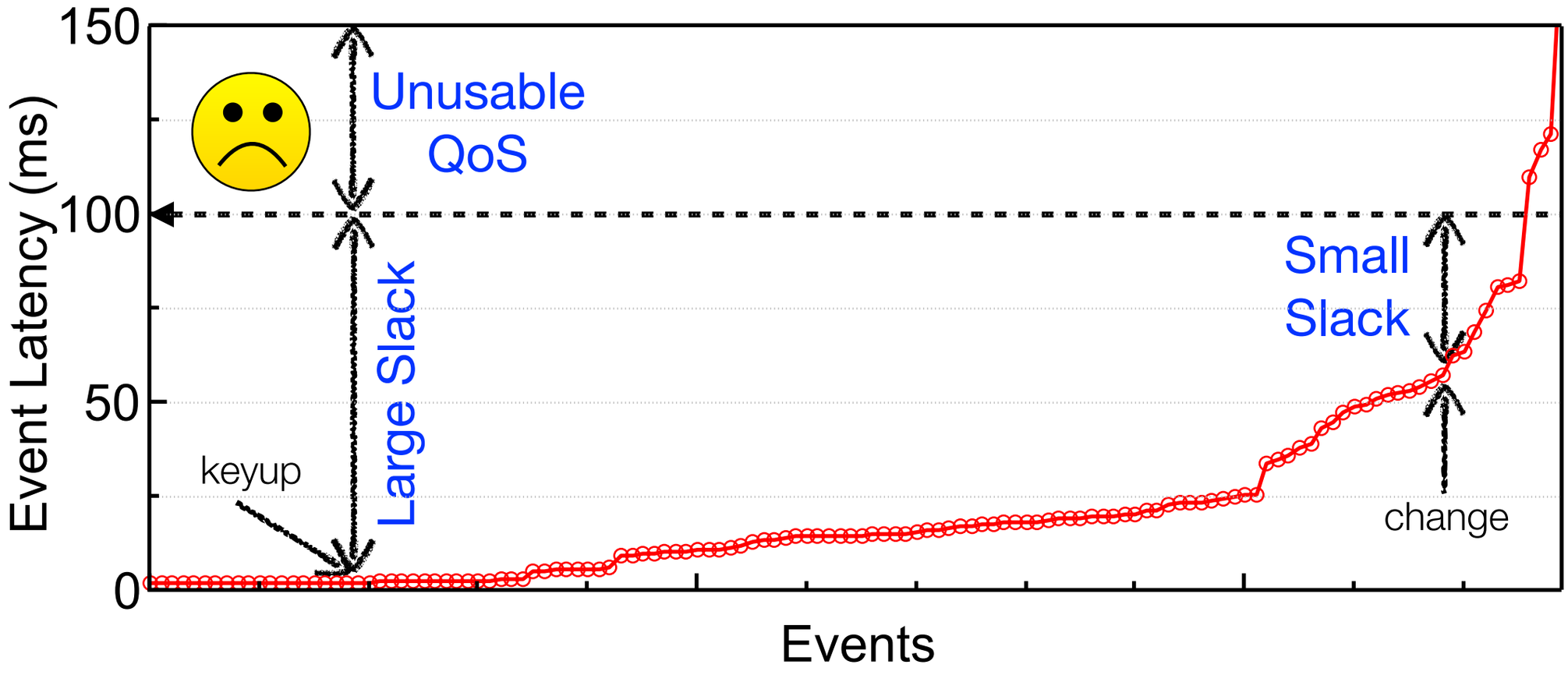

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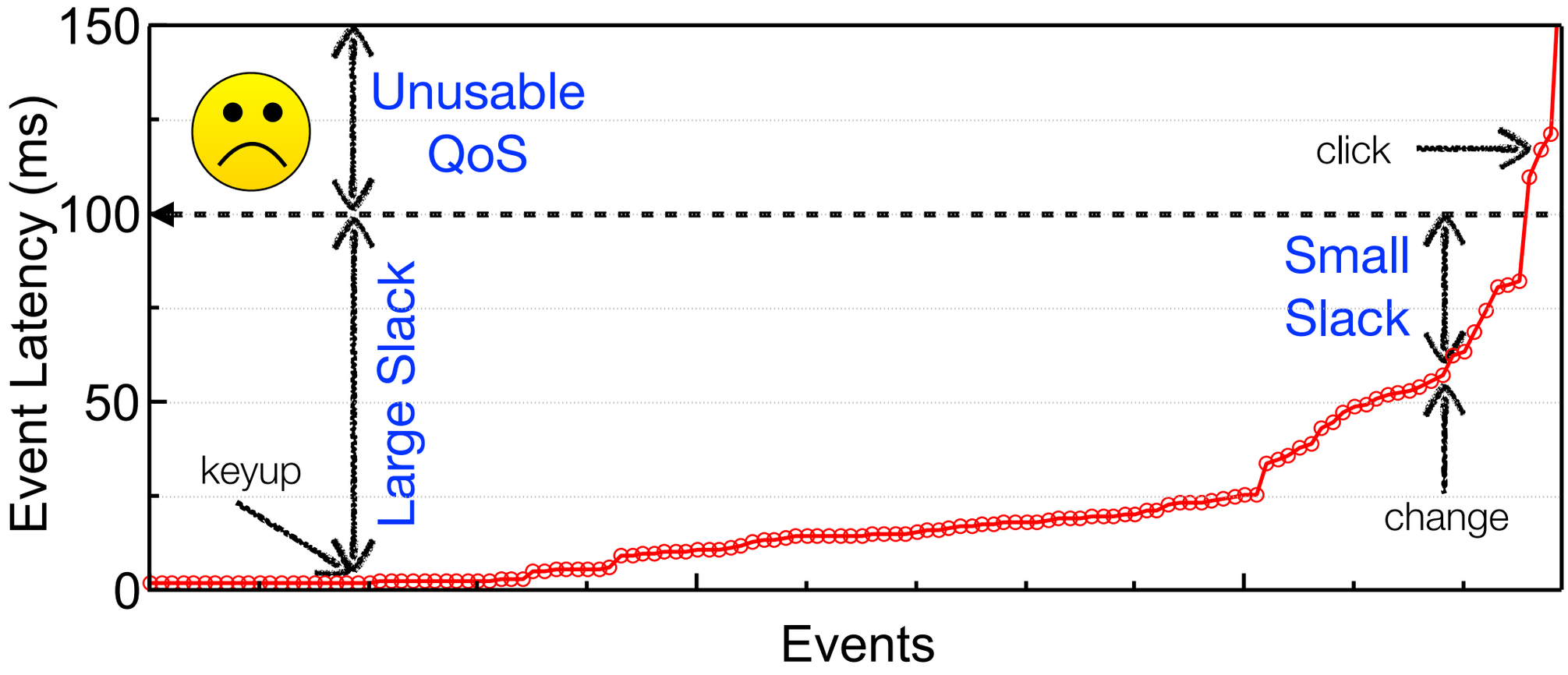

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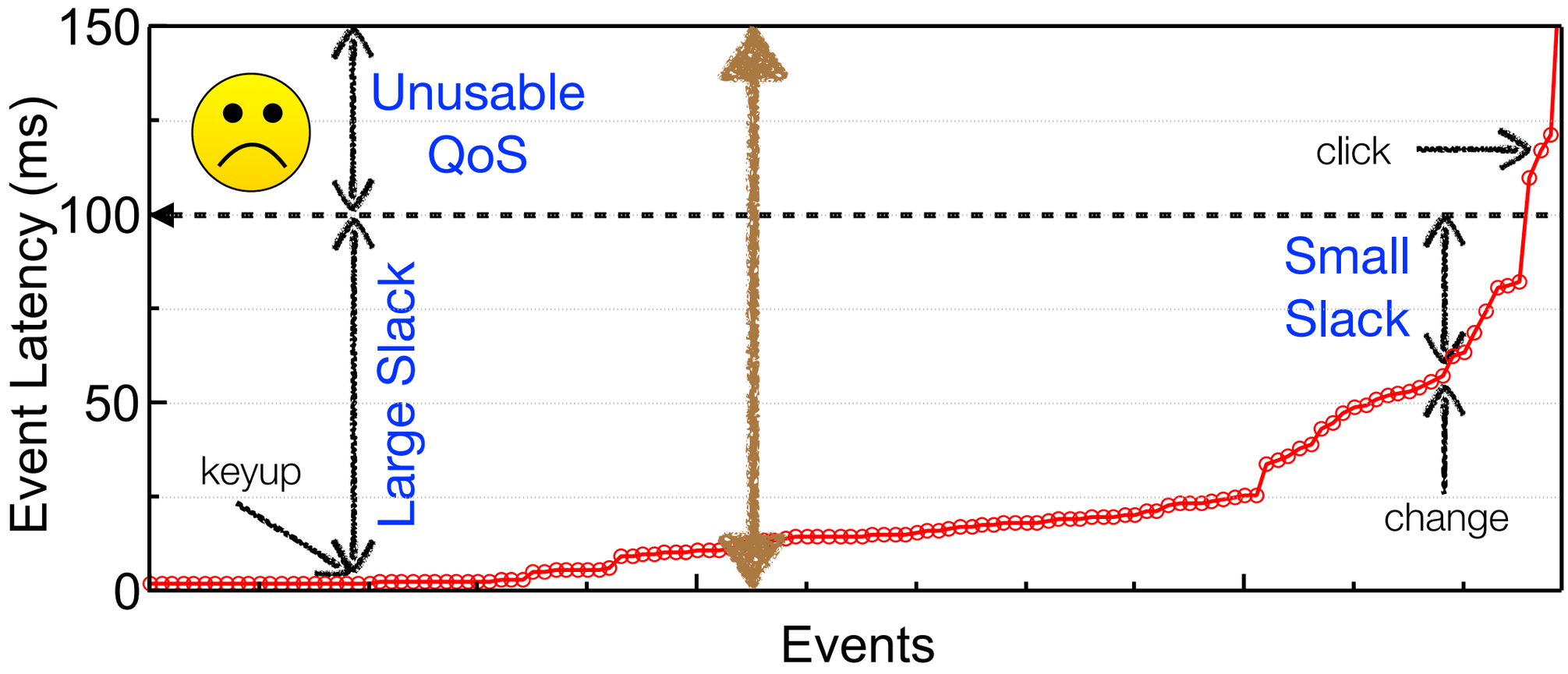

- Wide distribution of event latencies. Events exhibit different slacks.
  - How to exploit different slacks for different events?

Event-Based Scheduler (EBS) Overview

- **Goal**: Find the most energy-efficient architectural configuration that meets the QoS target for each event

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Thread Scheduling

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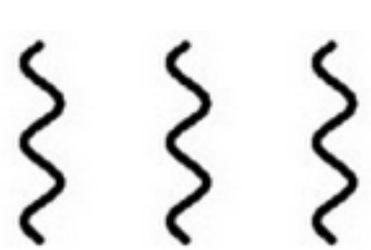

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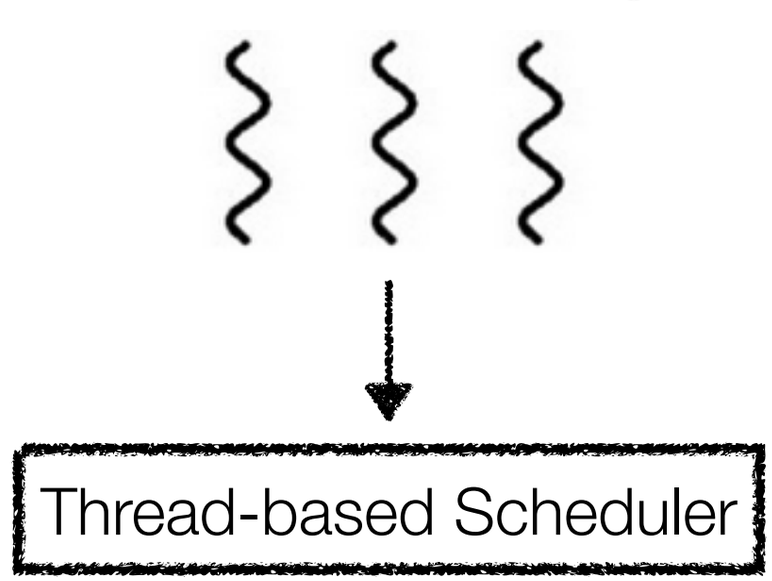

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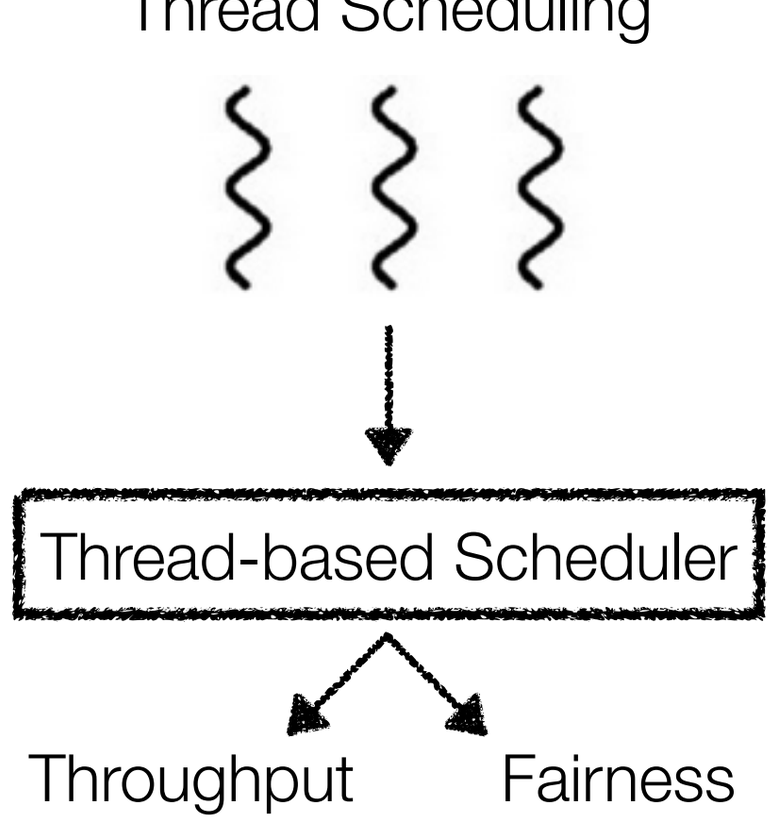

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Mobile applications

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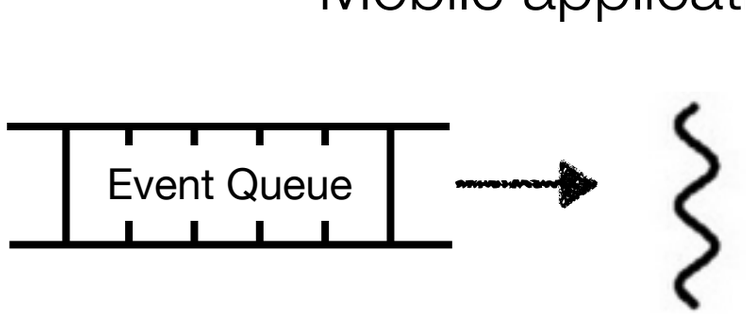

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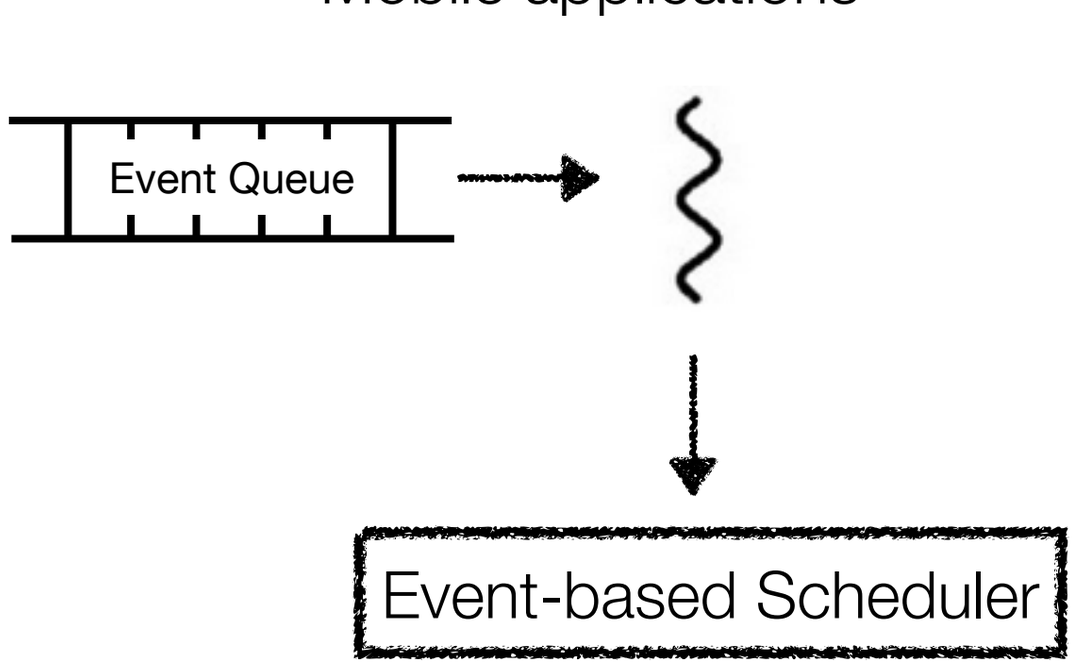

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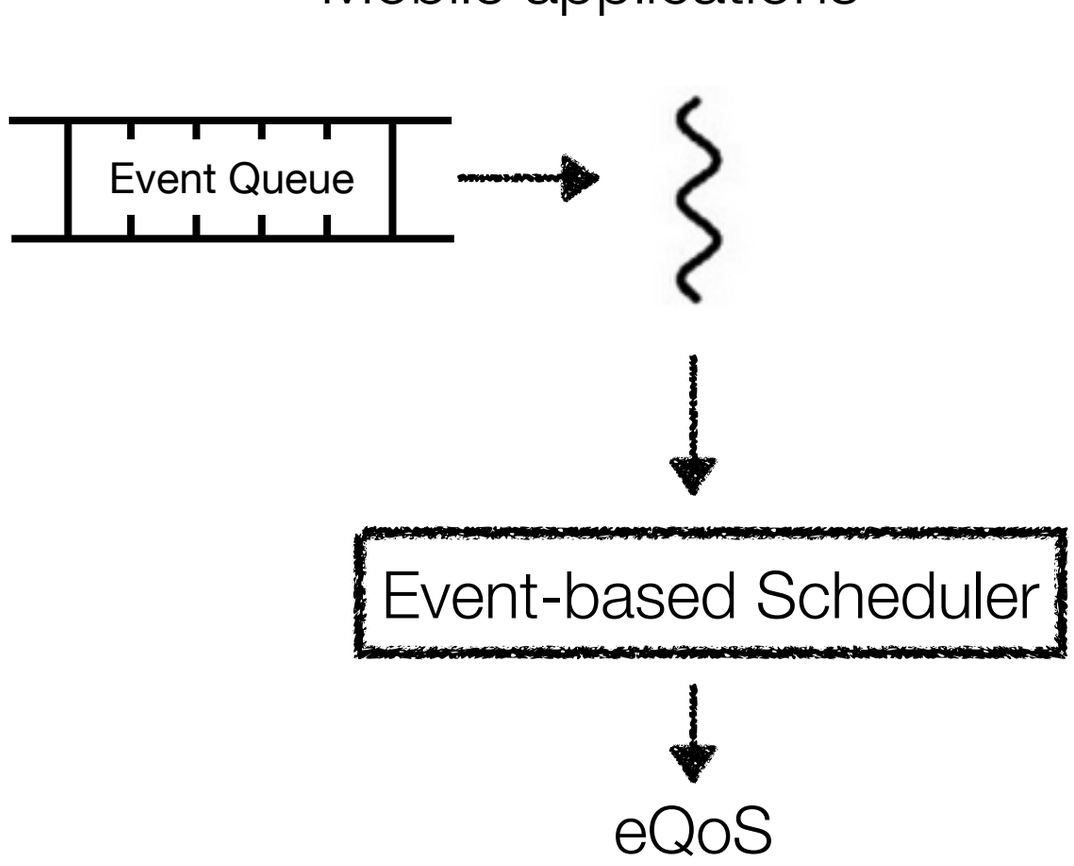

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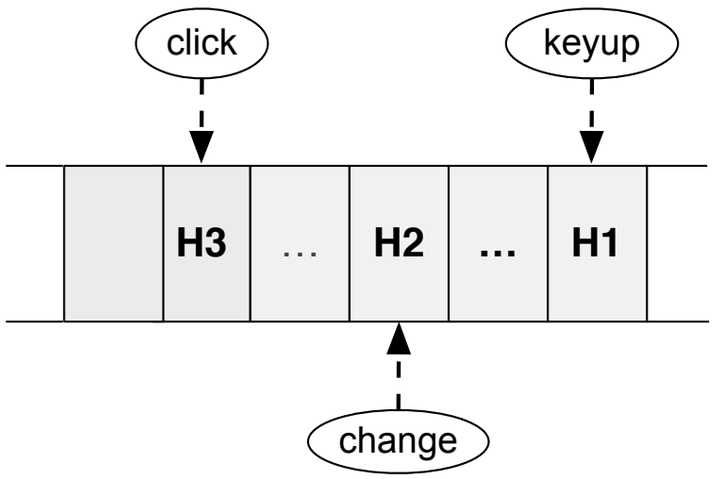
Event Queue



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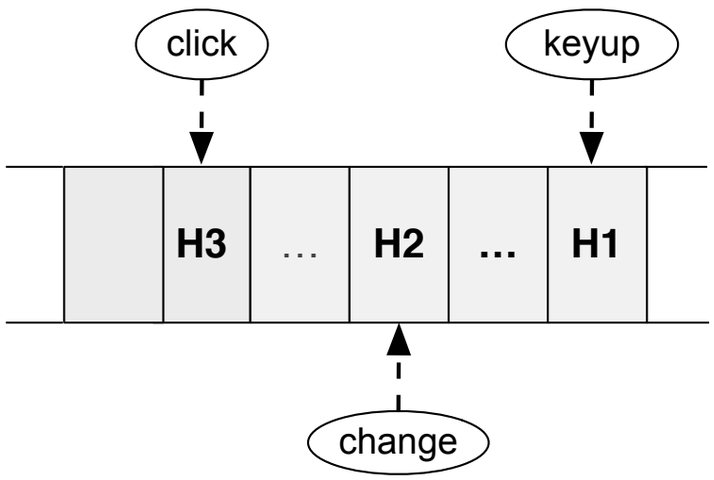
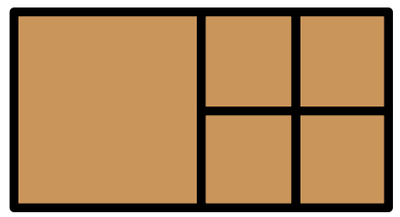


Big/Little Hardware



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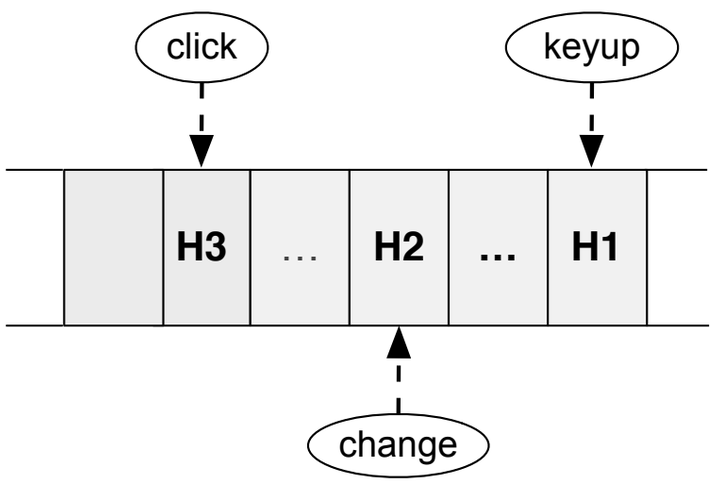
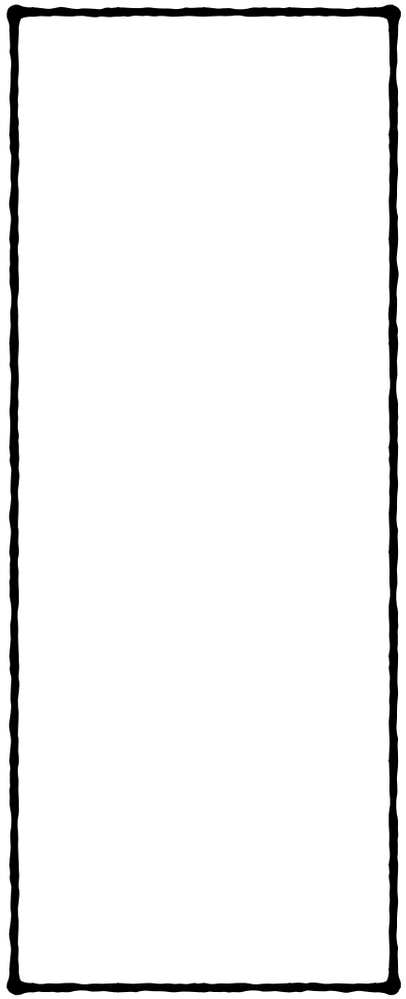


Event-Based Scheduler



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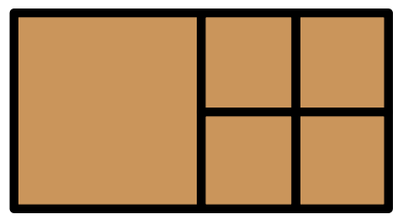

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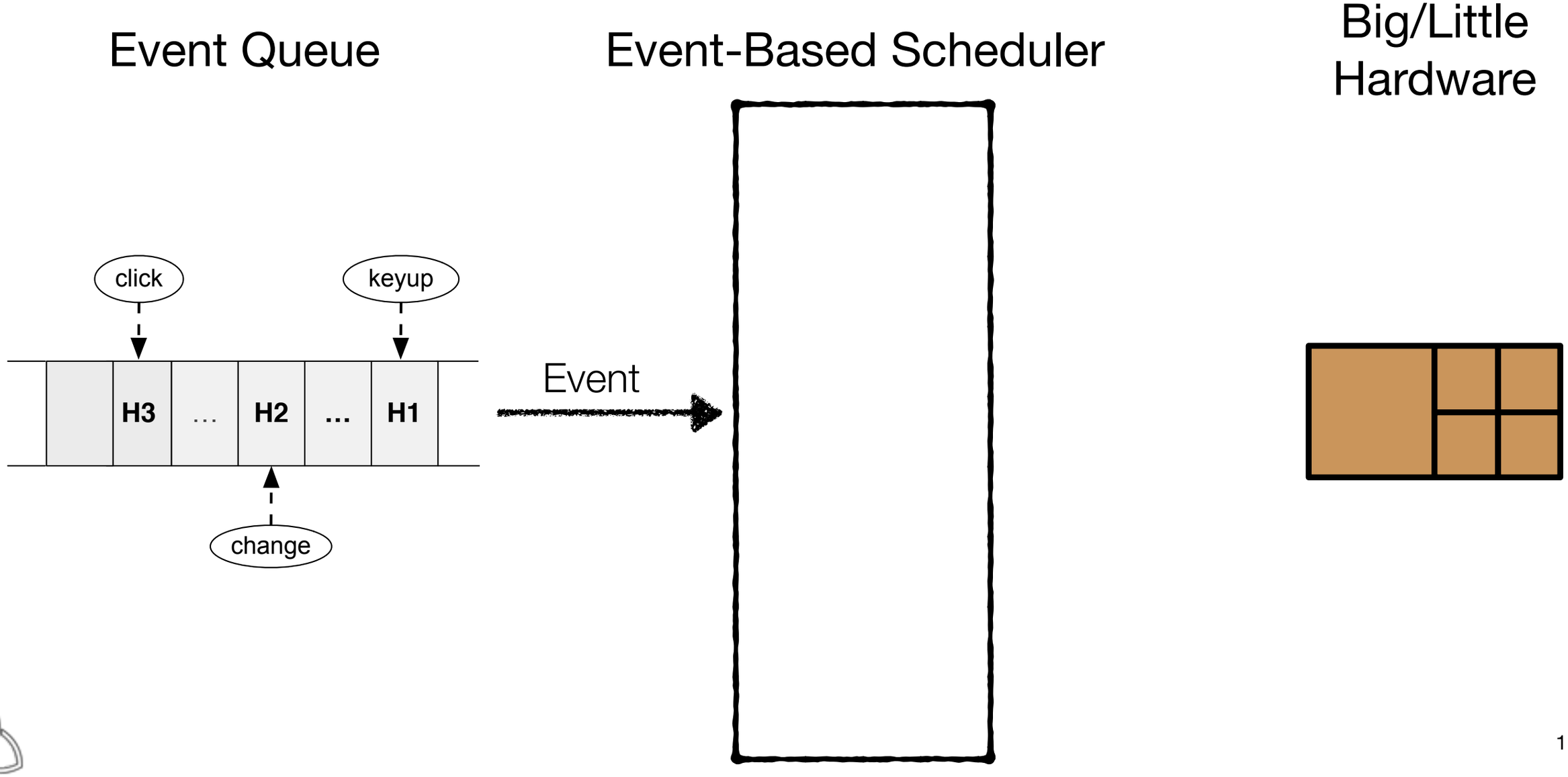

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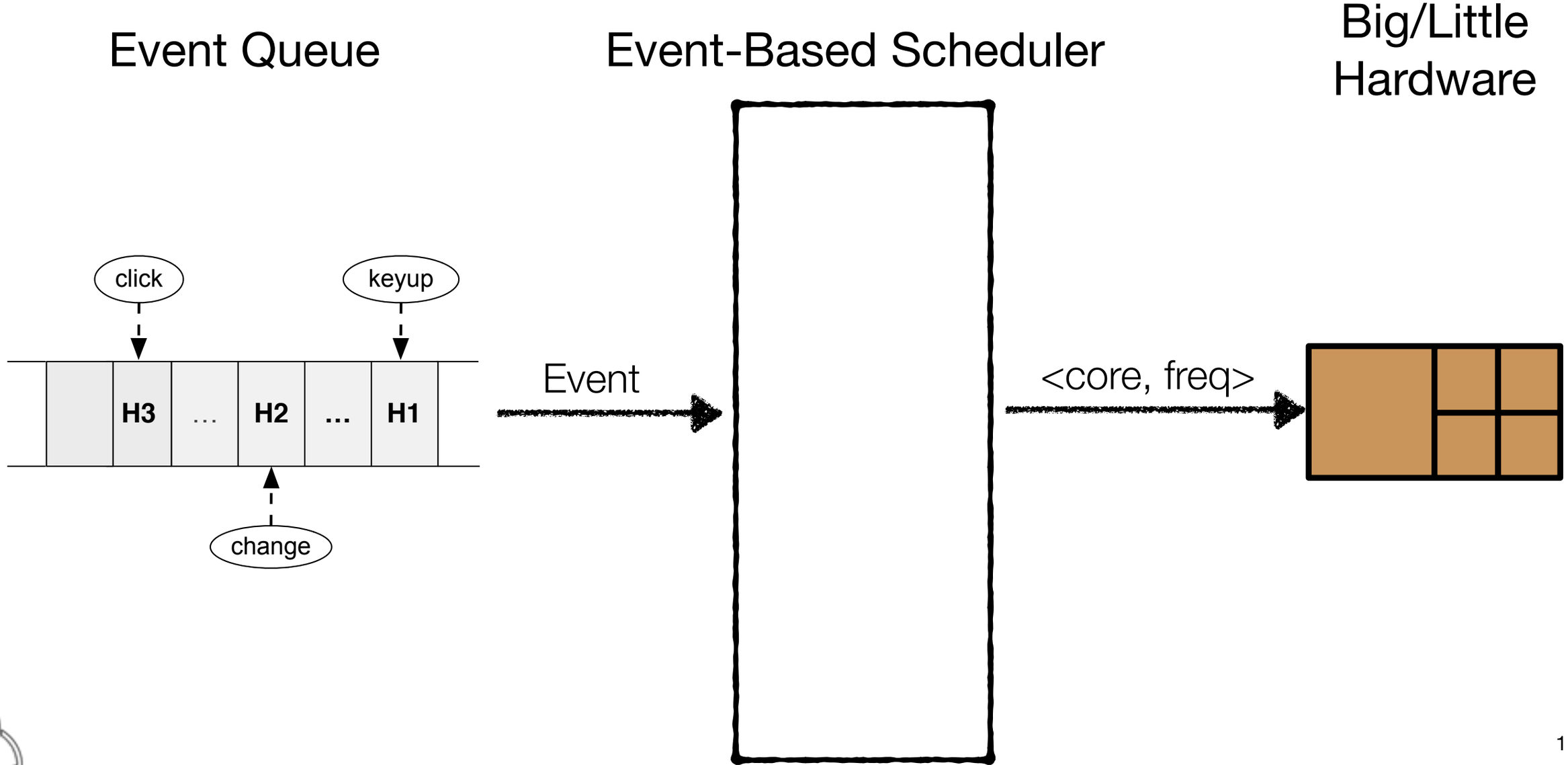

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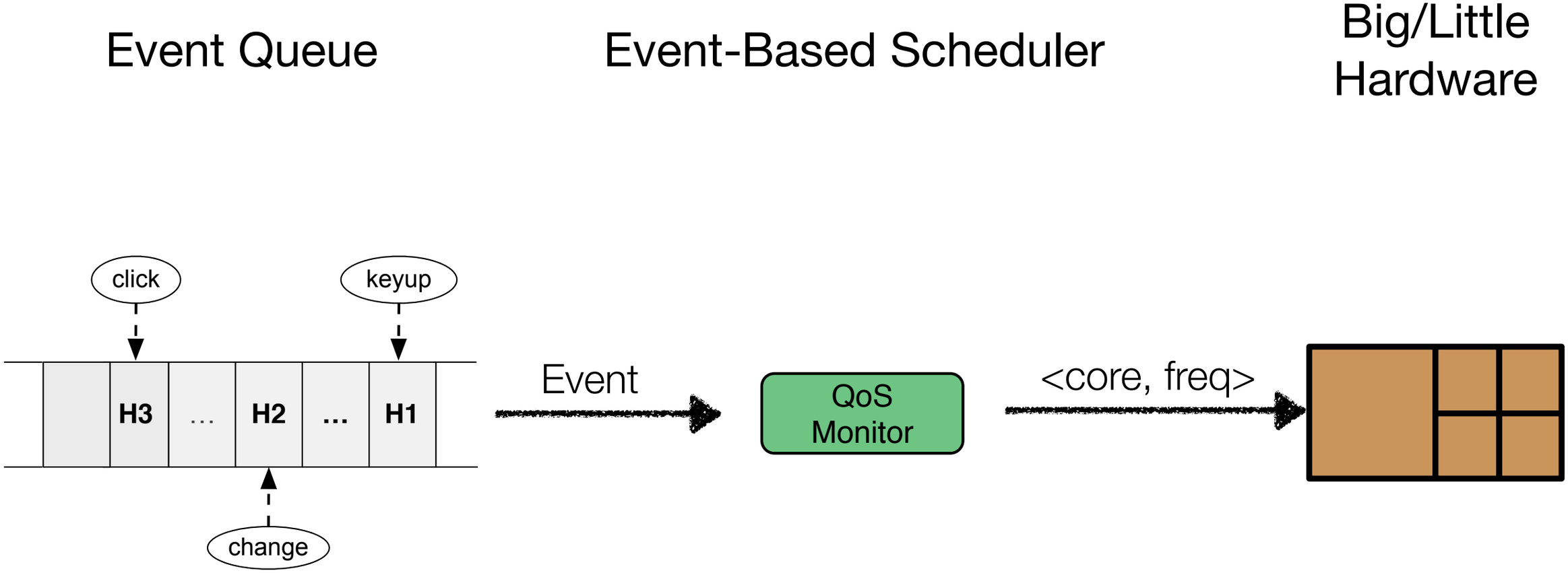

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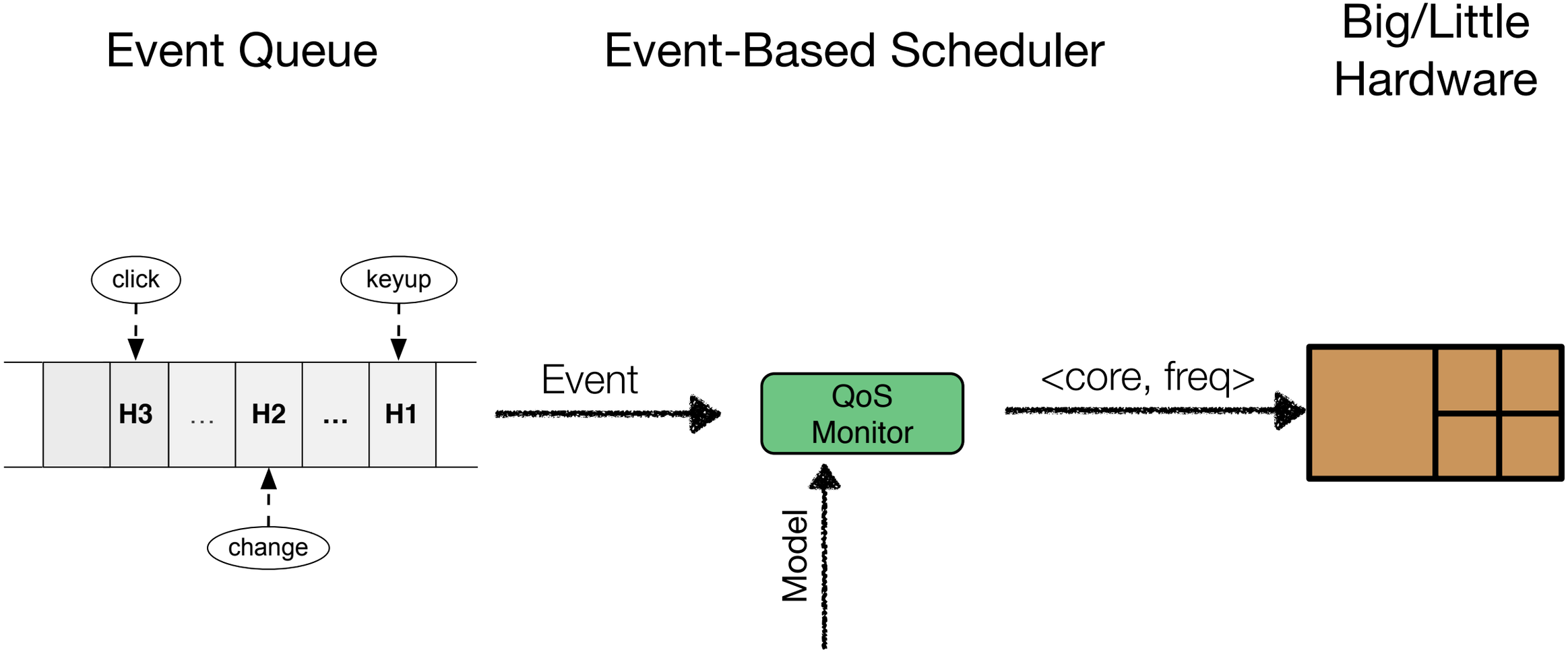

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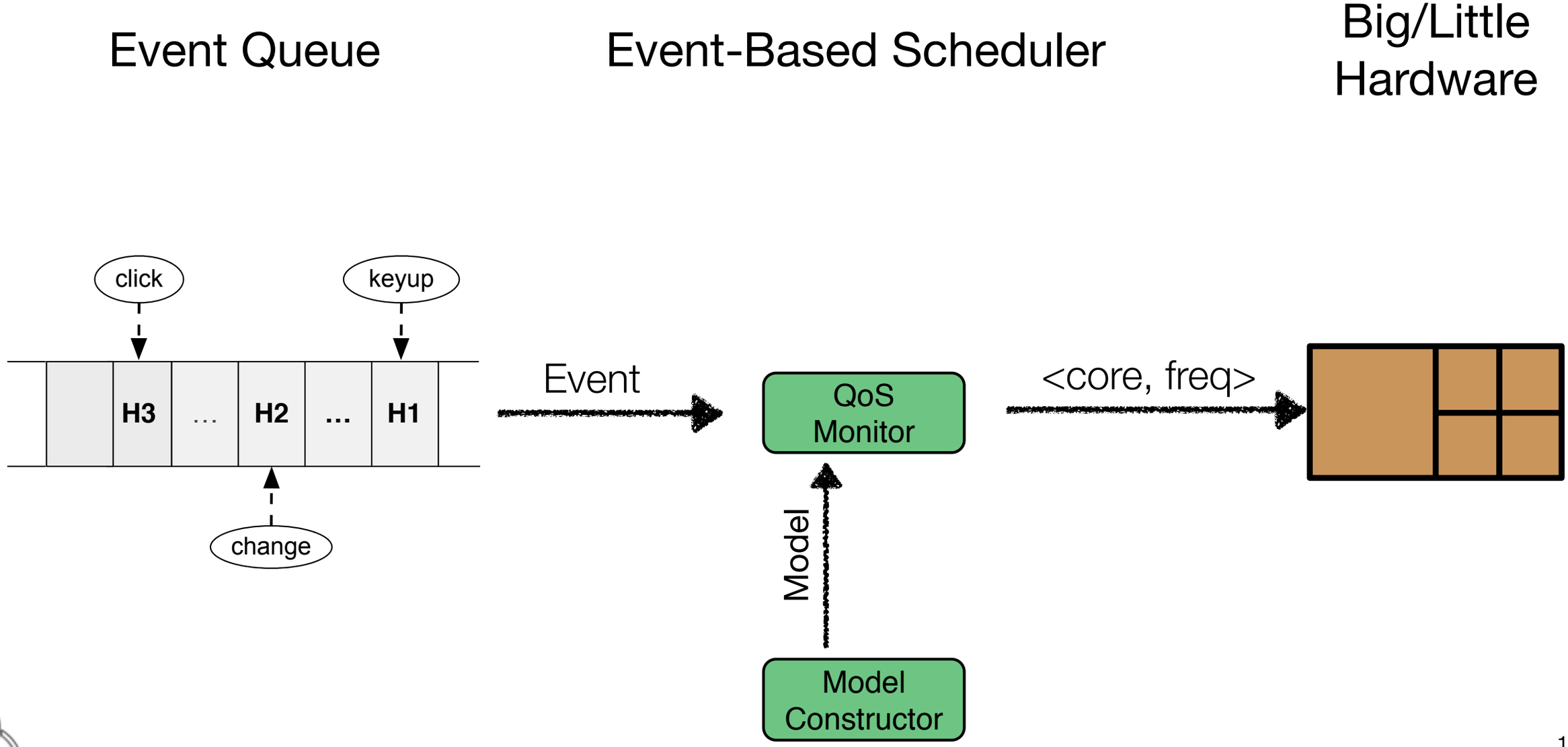

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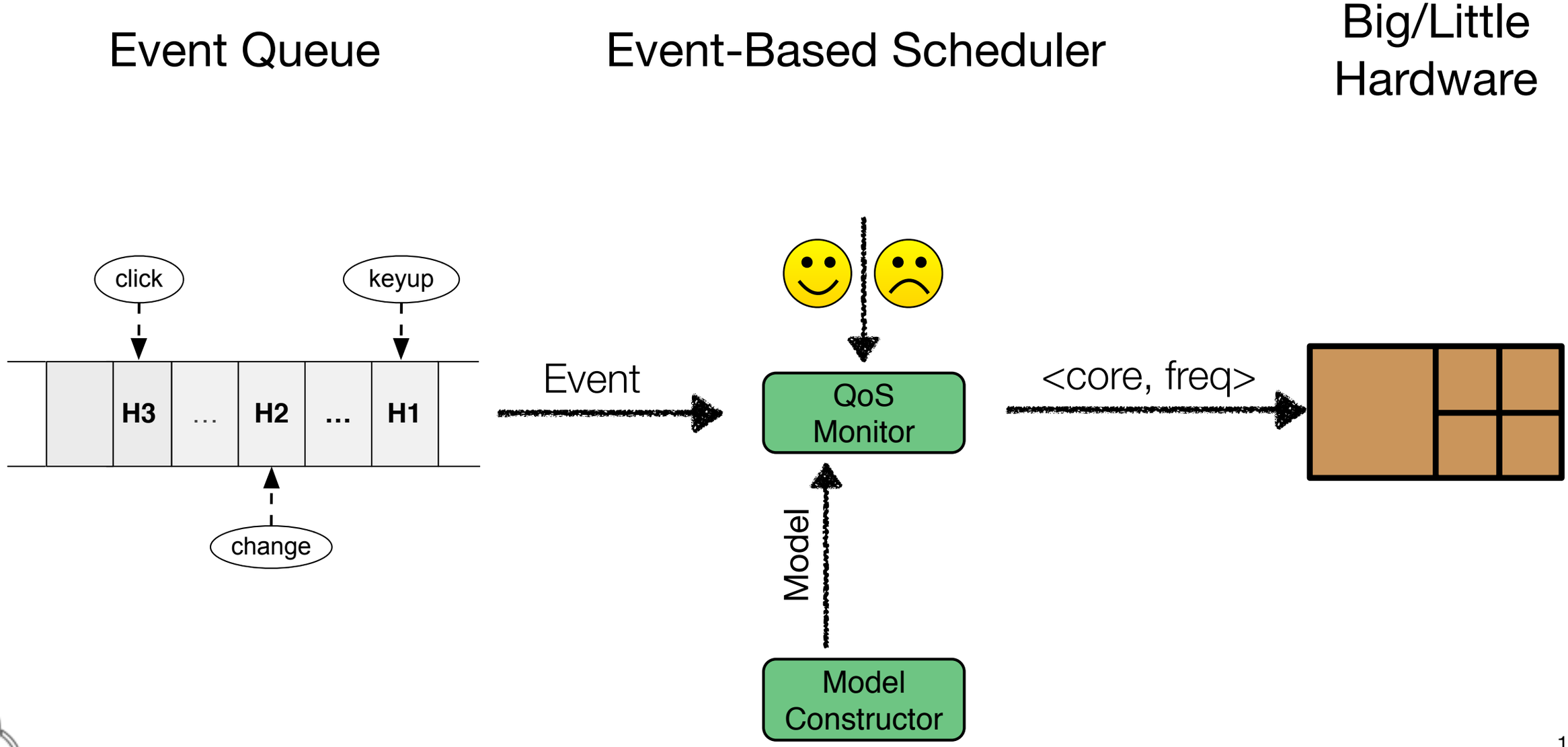

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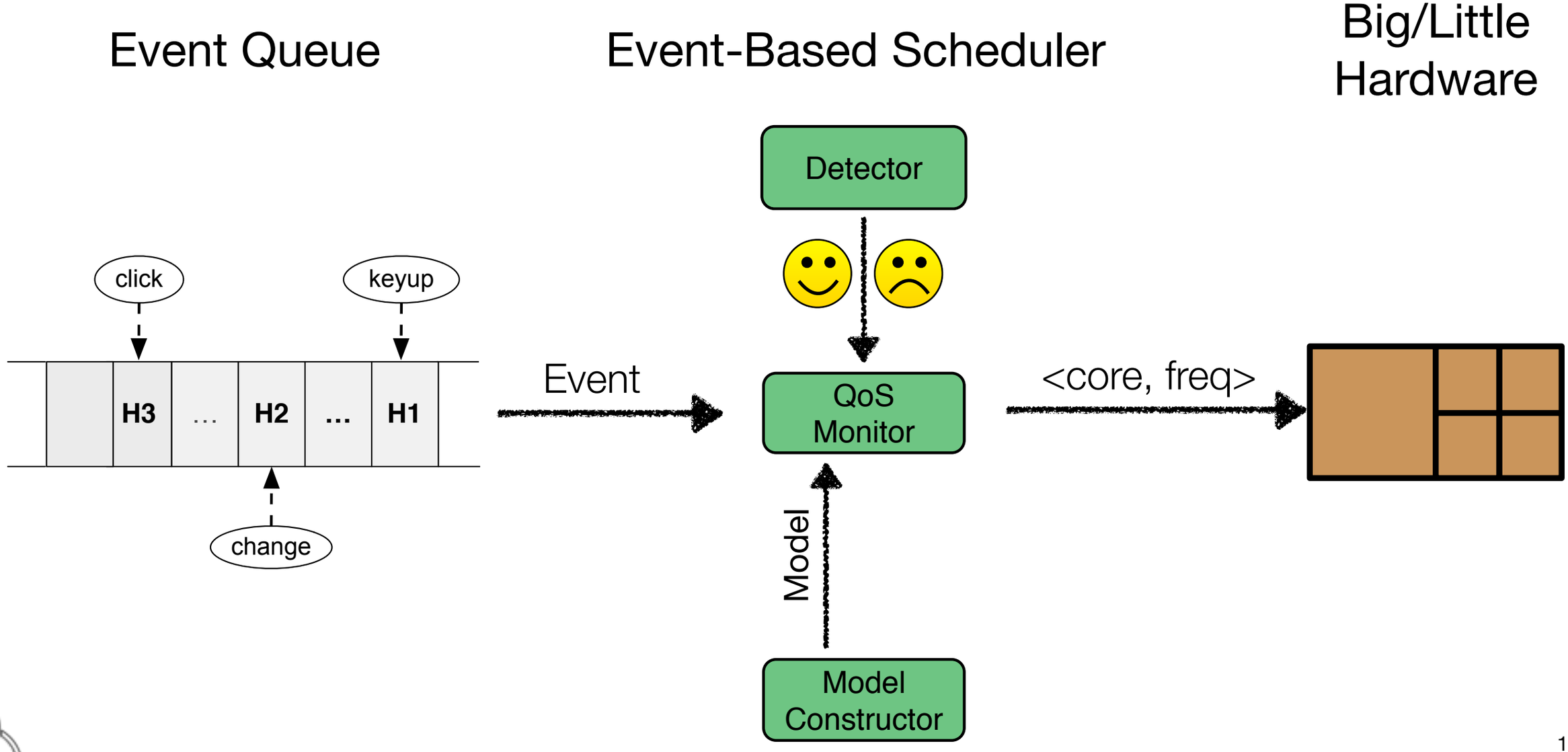

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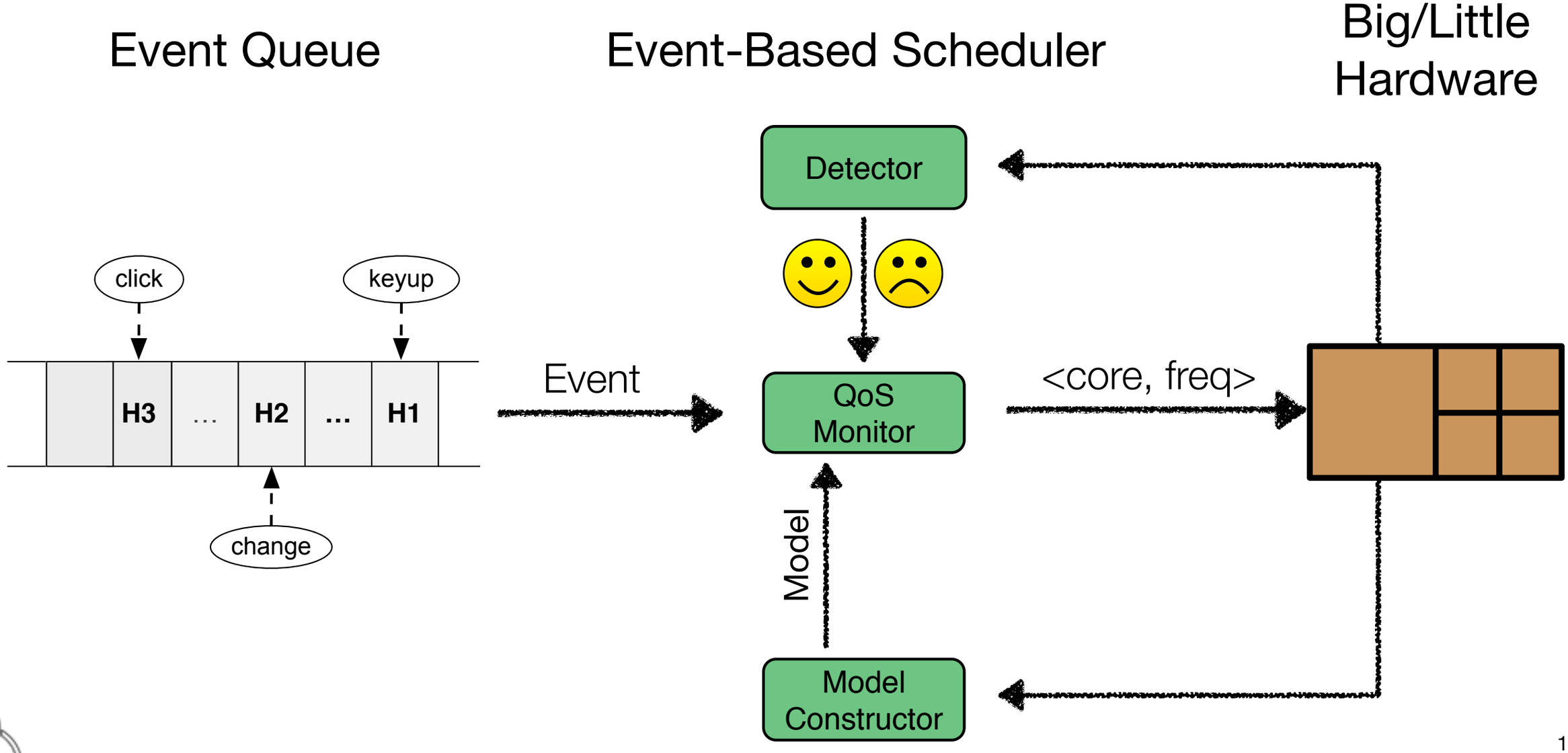

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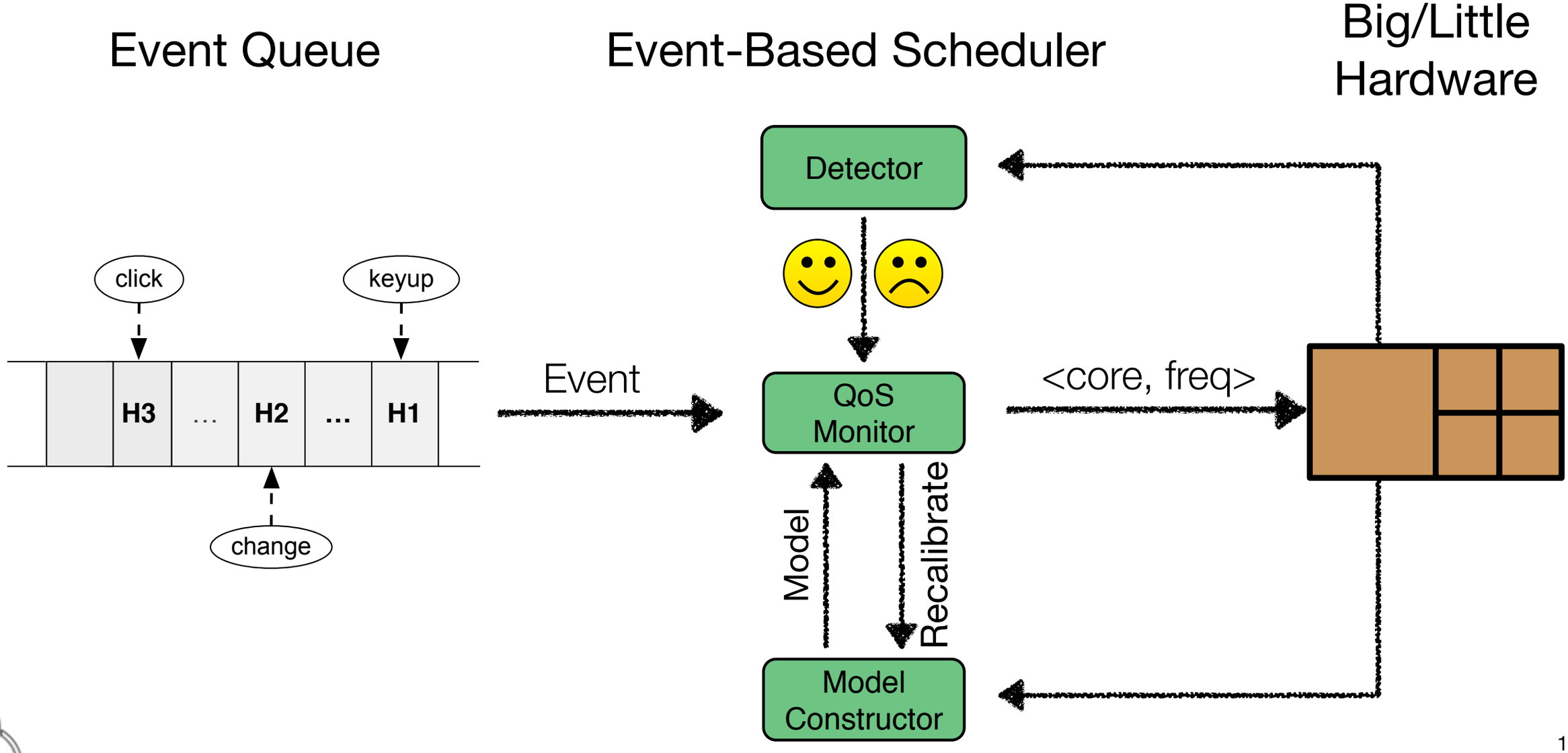

How the Model Constructor Works

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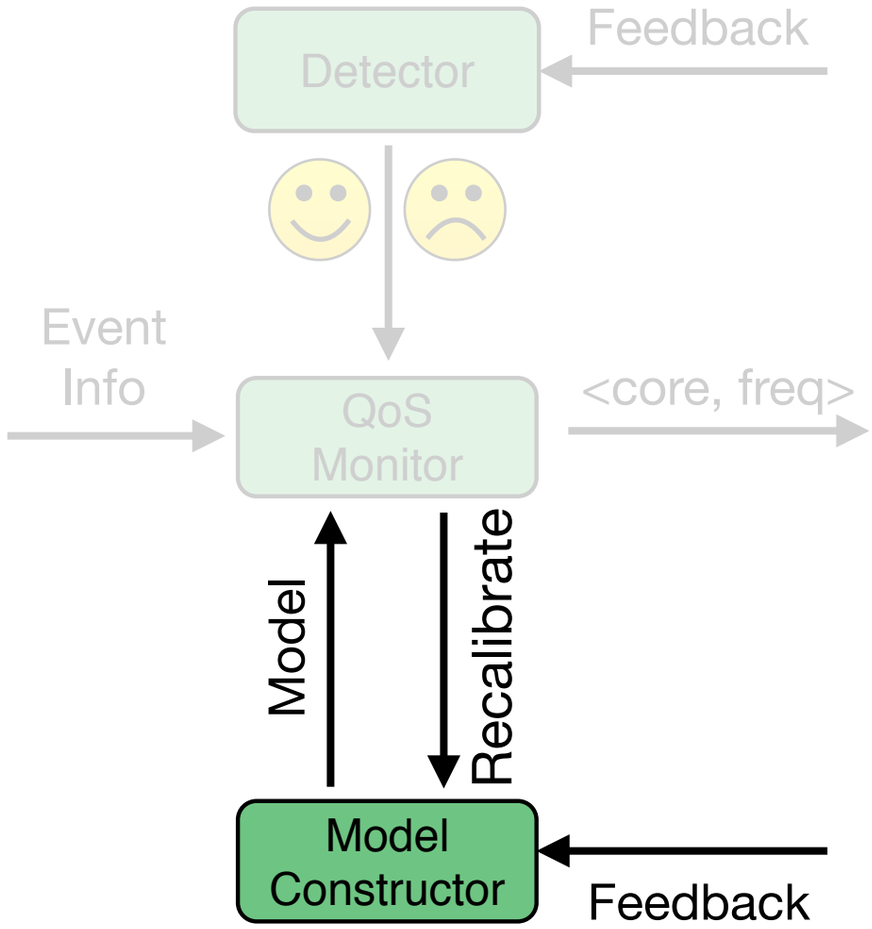

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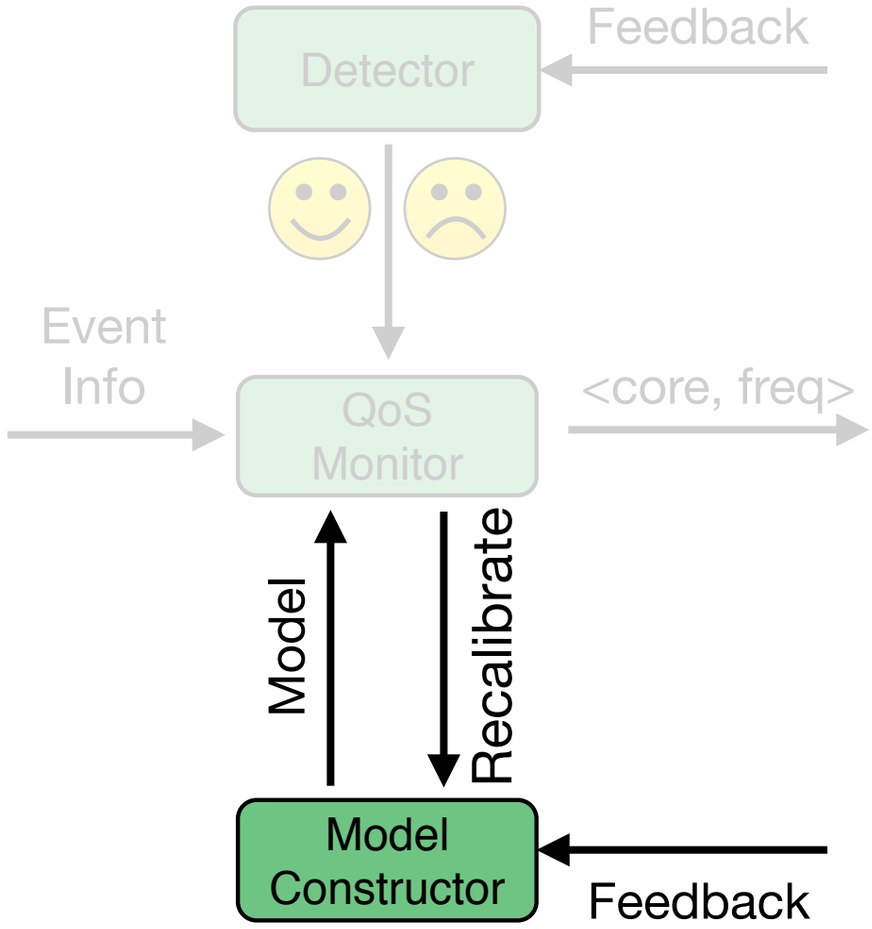

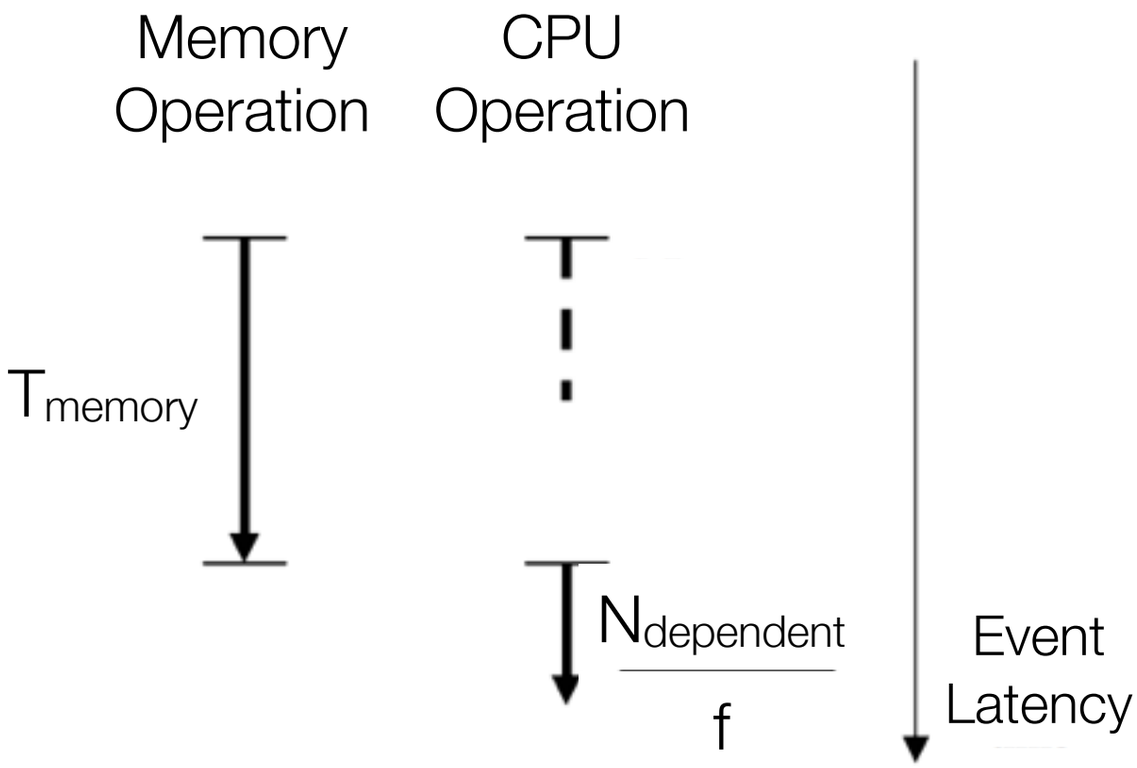

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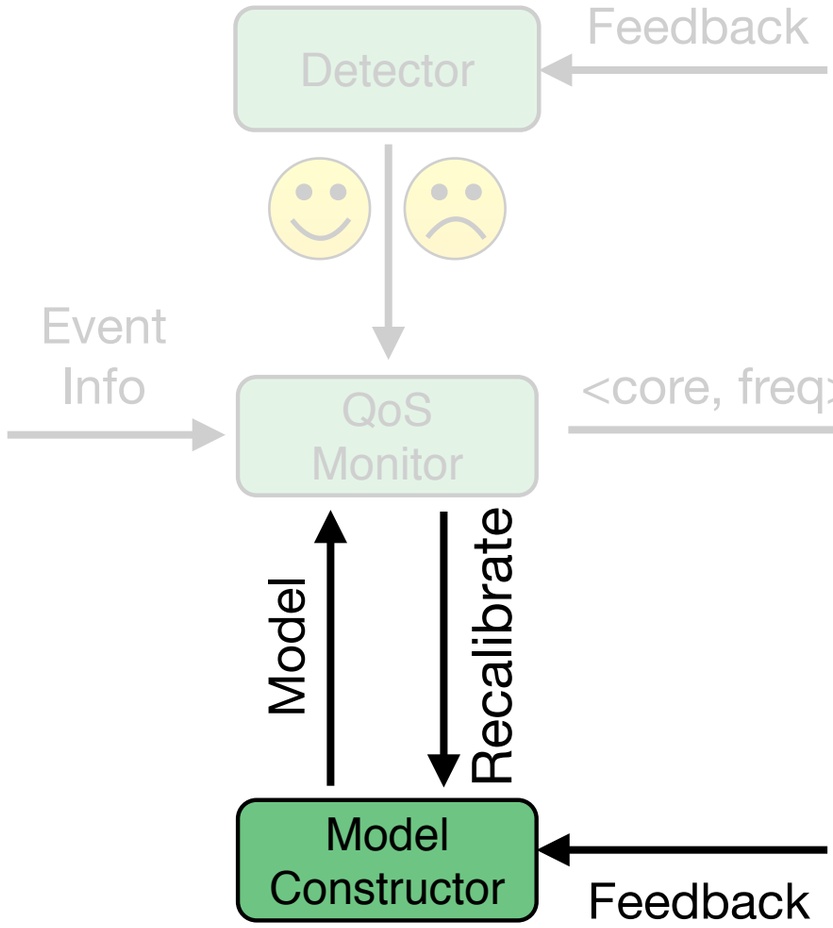

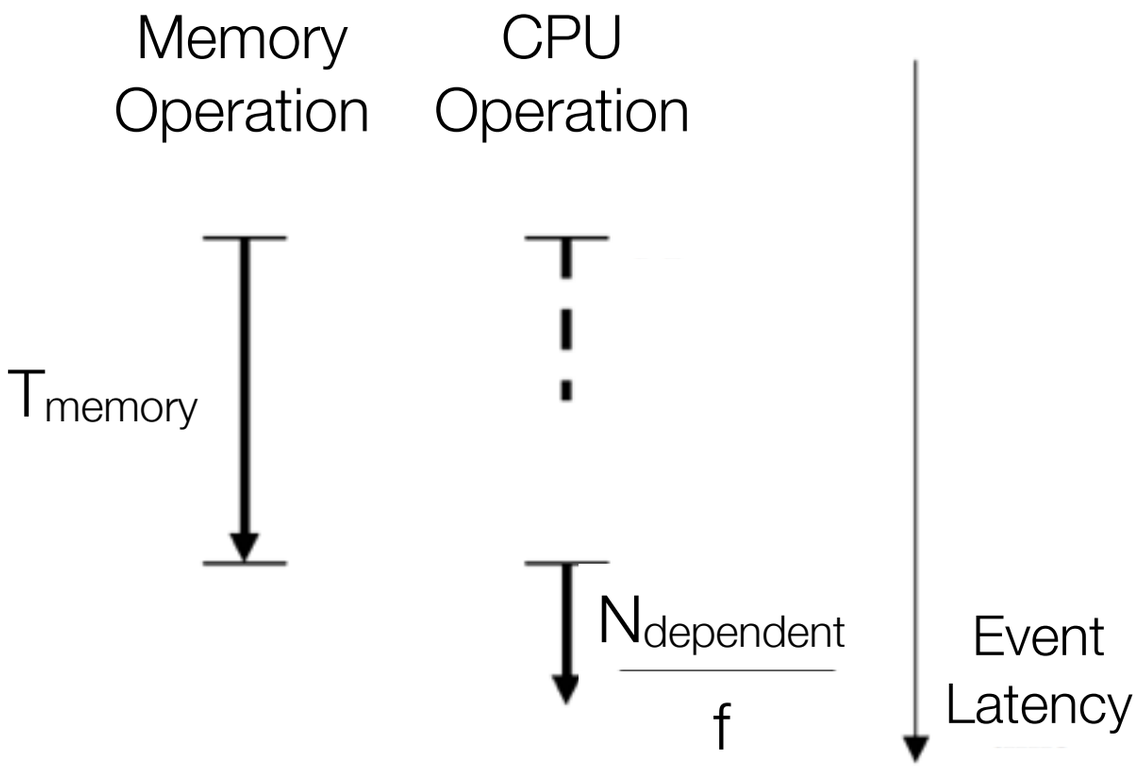

Event Latency =

Xie, et al., Compile-Time Dynamic Voltage Scaling Settings: Opportunities and Limits, PLDI'03

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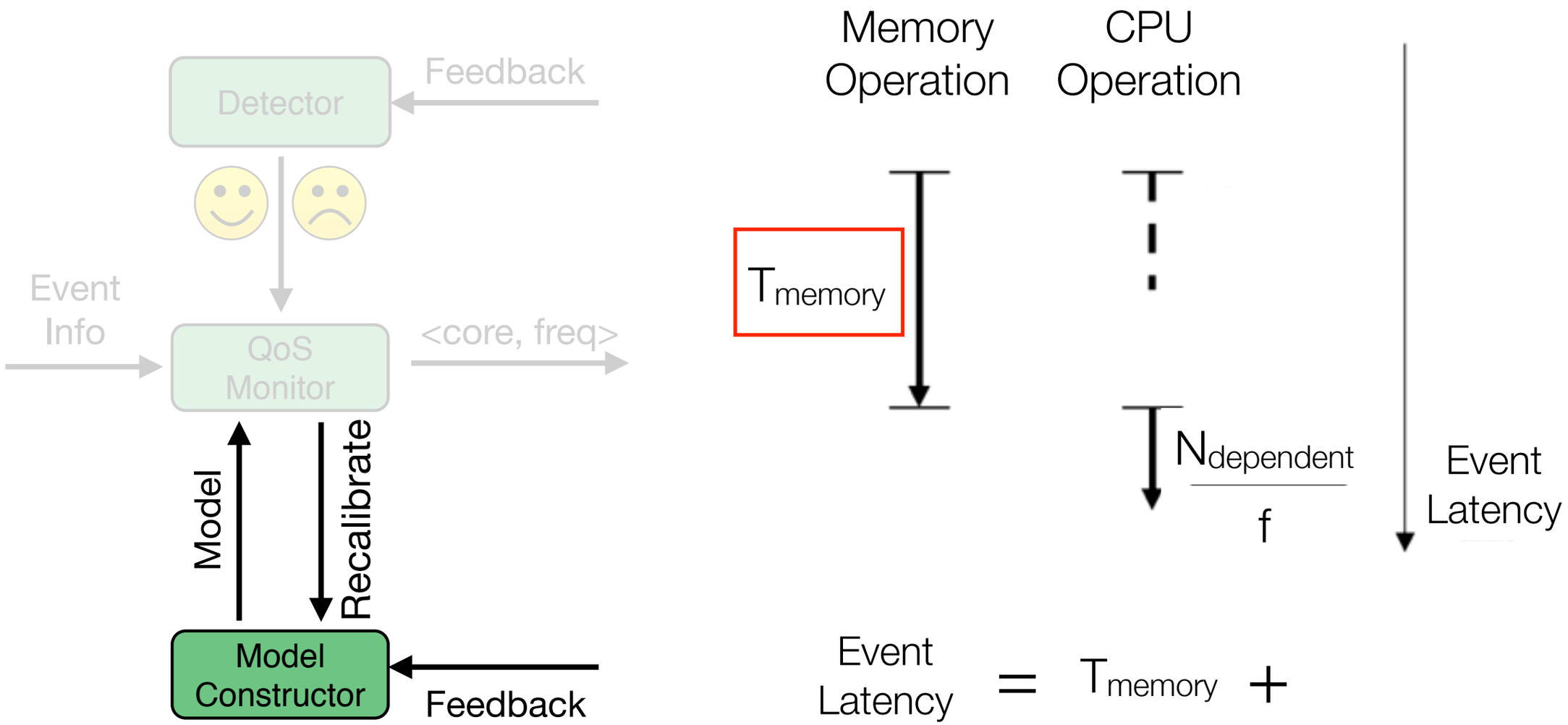

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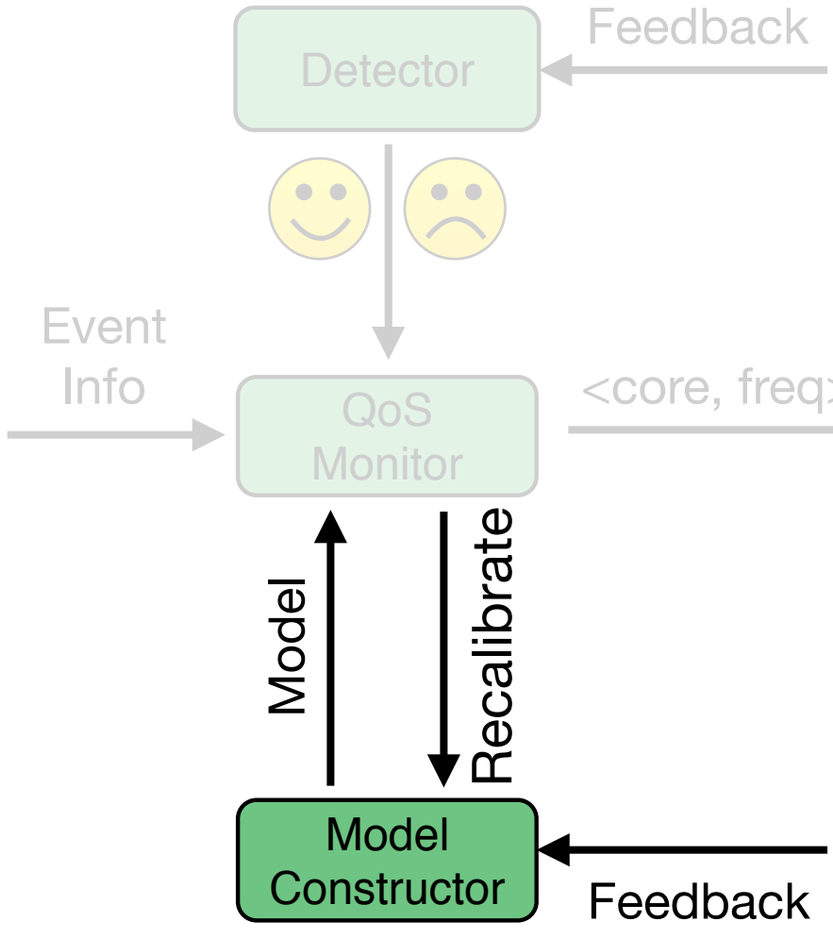

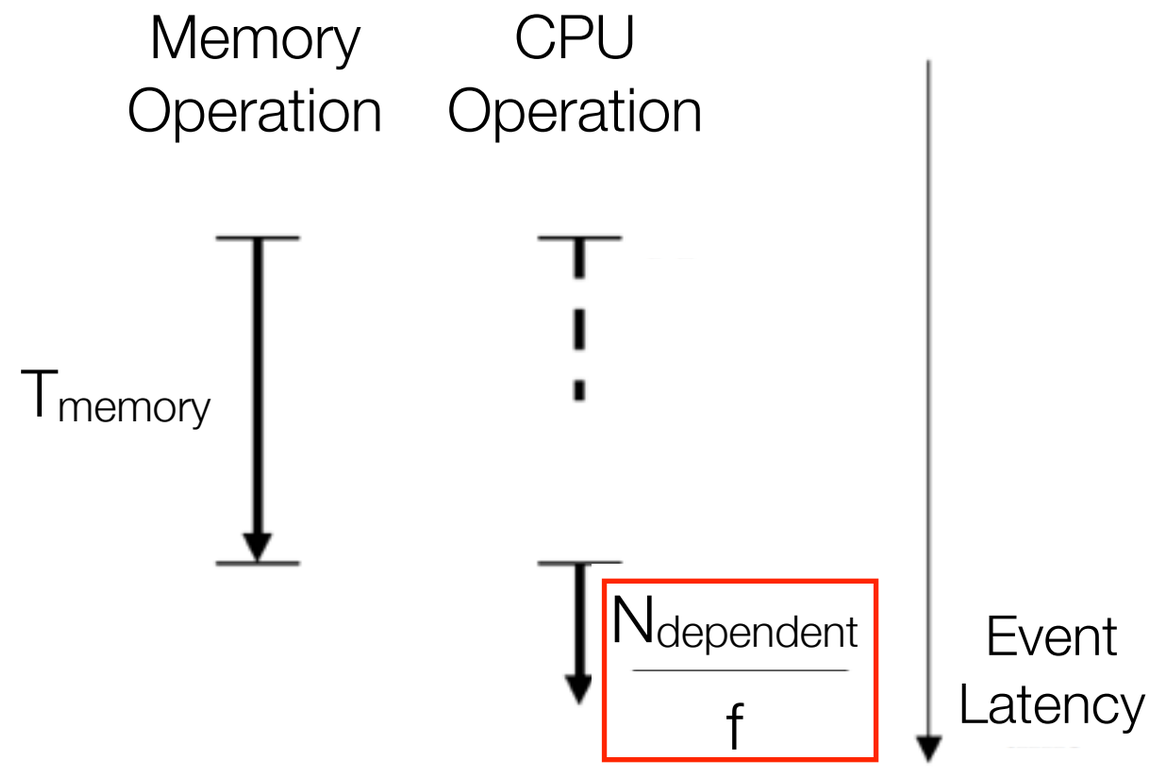

$$\text{Event Latency} = T_{memory} + N_{dependent} / f$$

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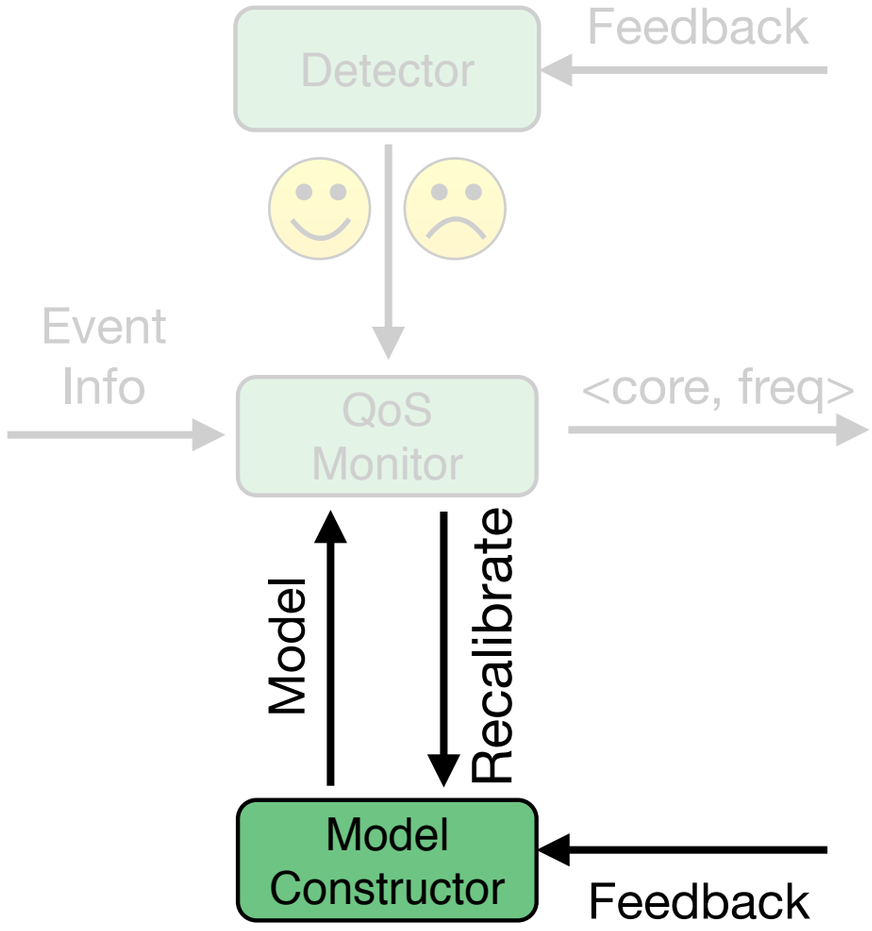

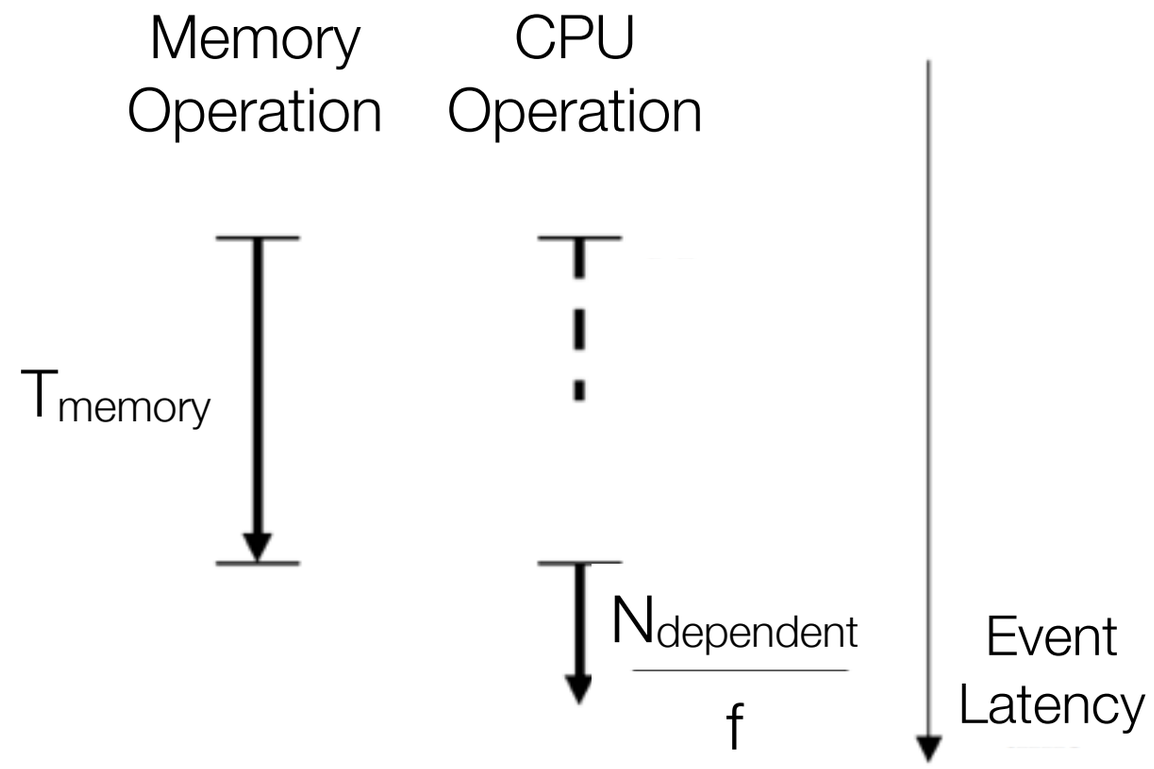

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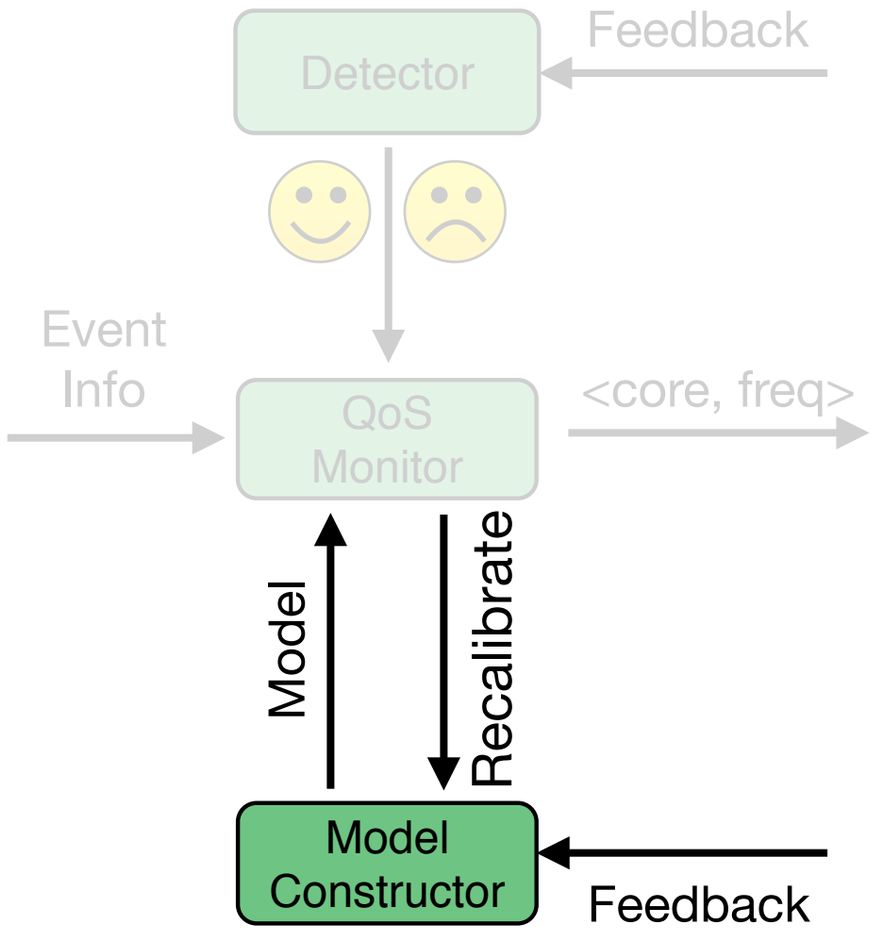

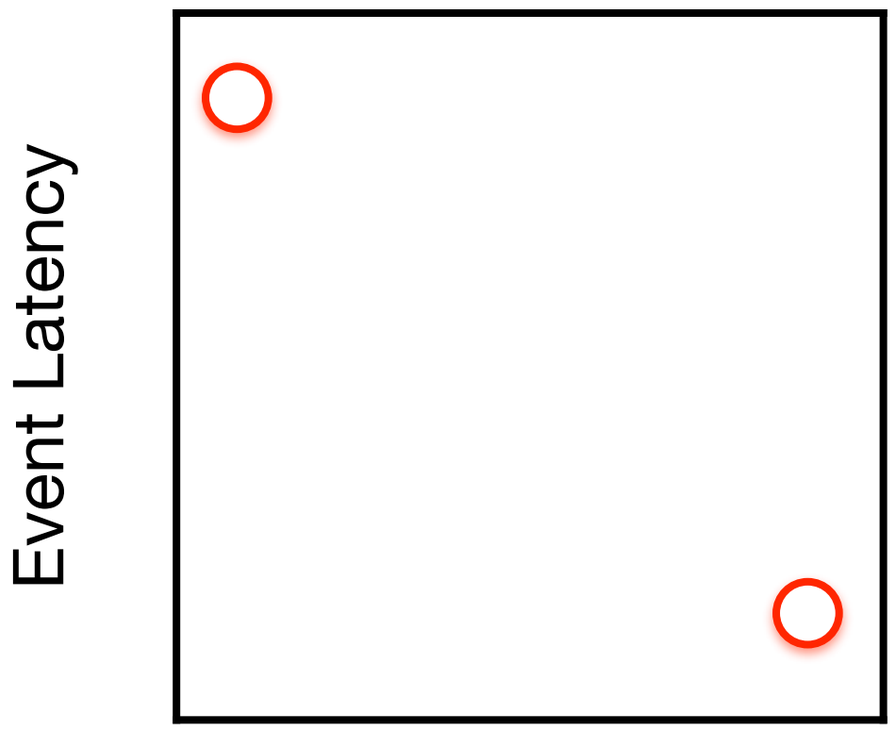

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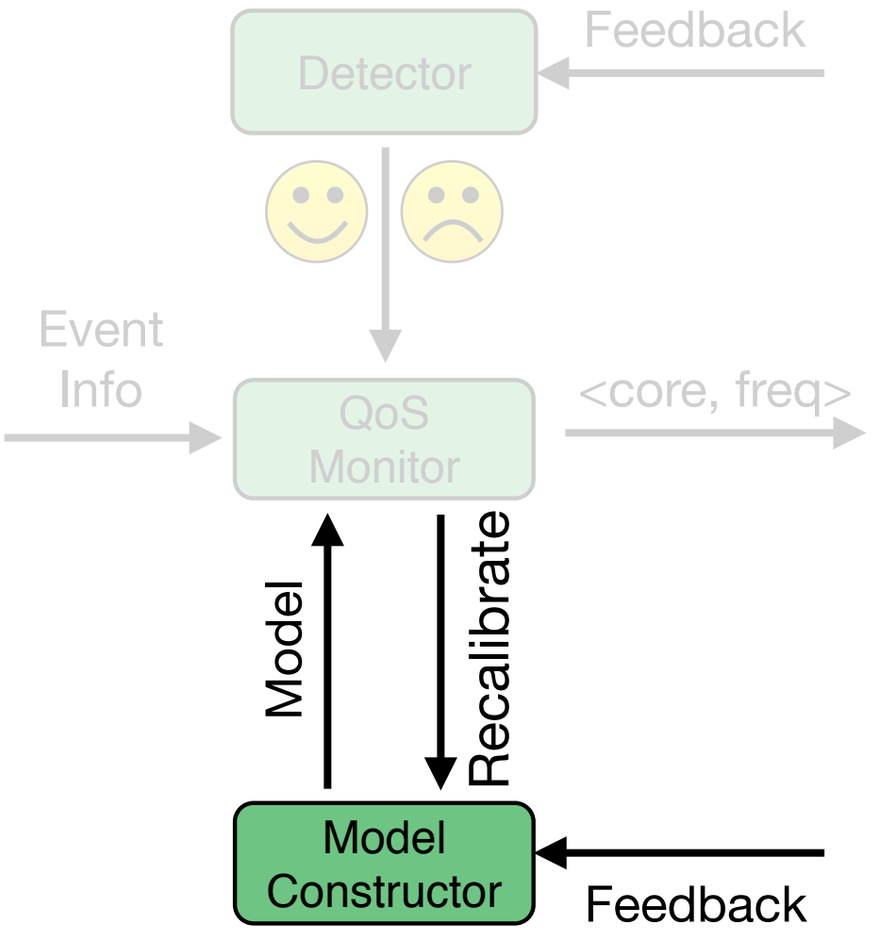
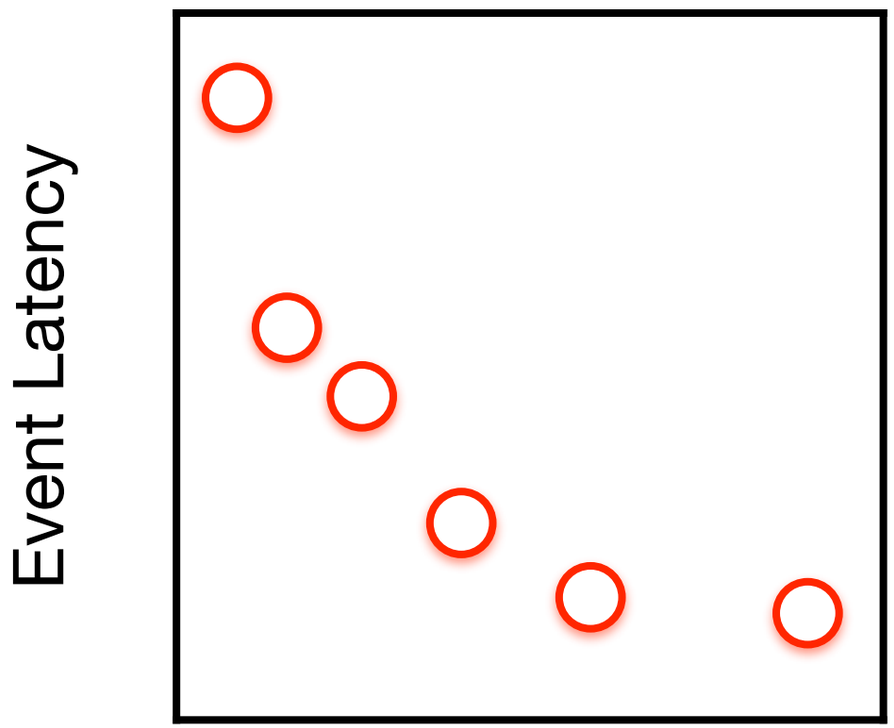
How the Model Constructor Works

- **Goal**: Estimate the event latency under each <core, freq> config



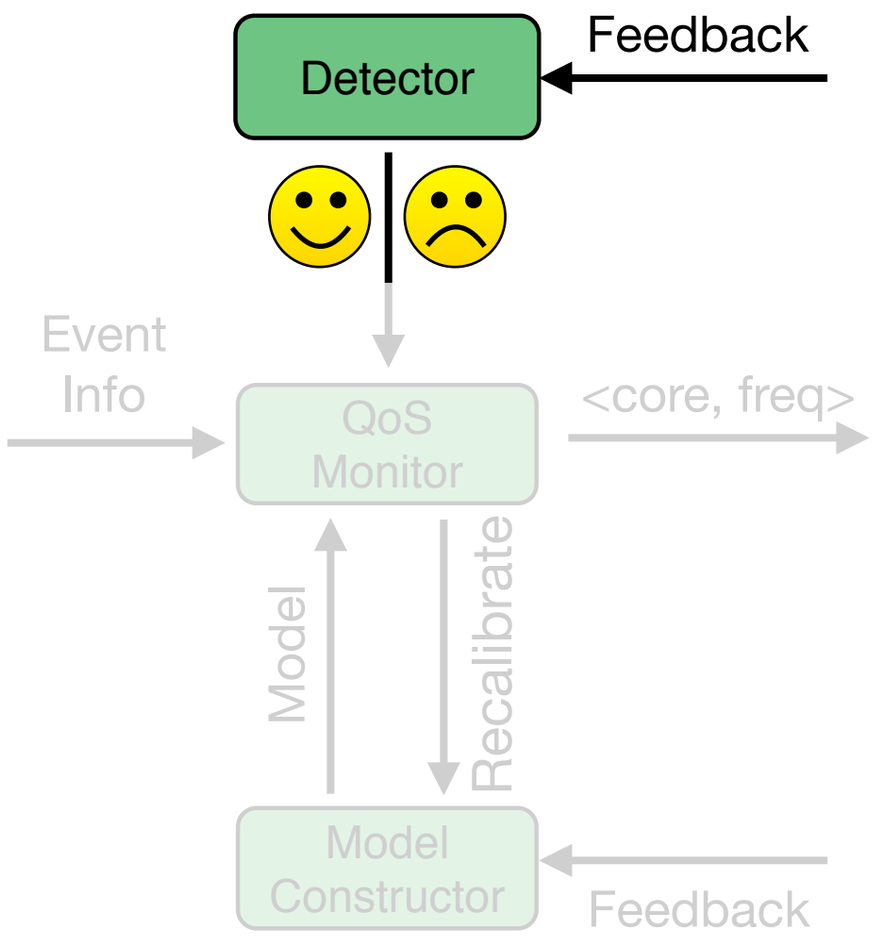


Frequency

$$\text{Event Latency} = T_{memory} + N_{dependent} / f$$

How the Detector Works

- **Goal**: Find the QoS target for each event



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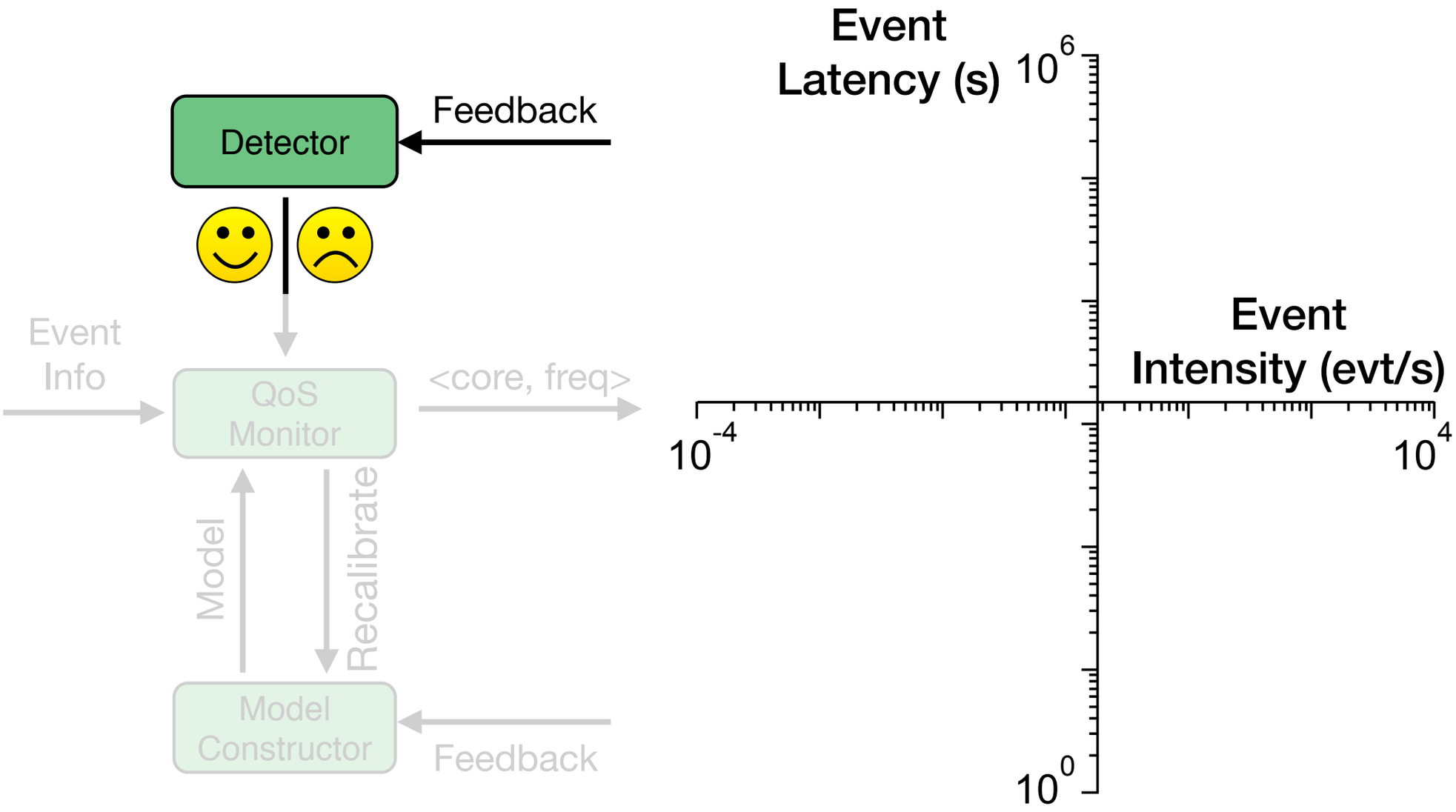

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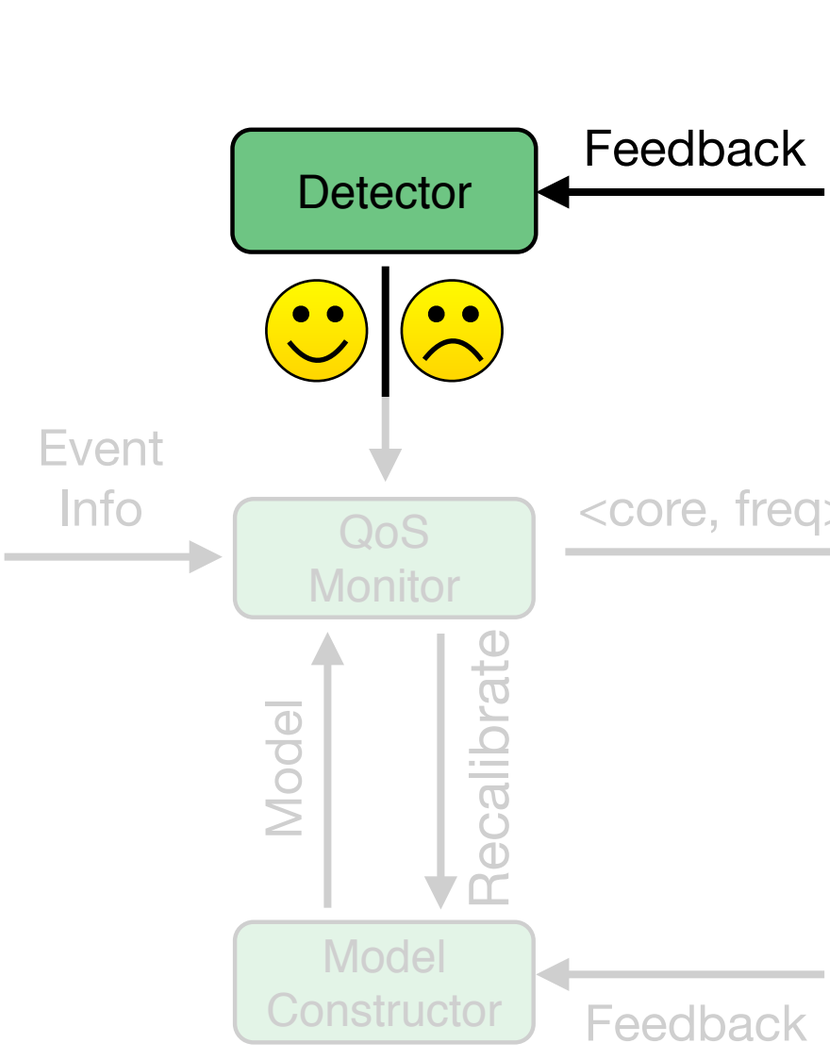

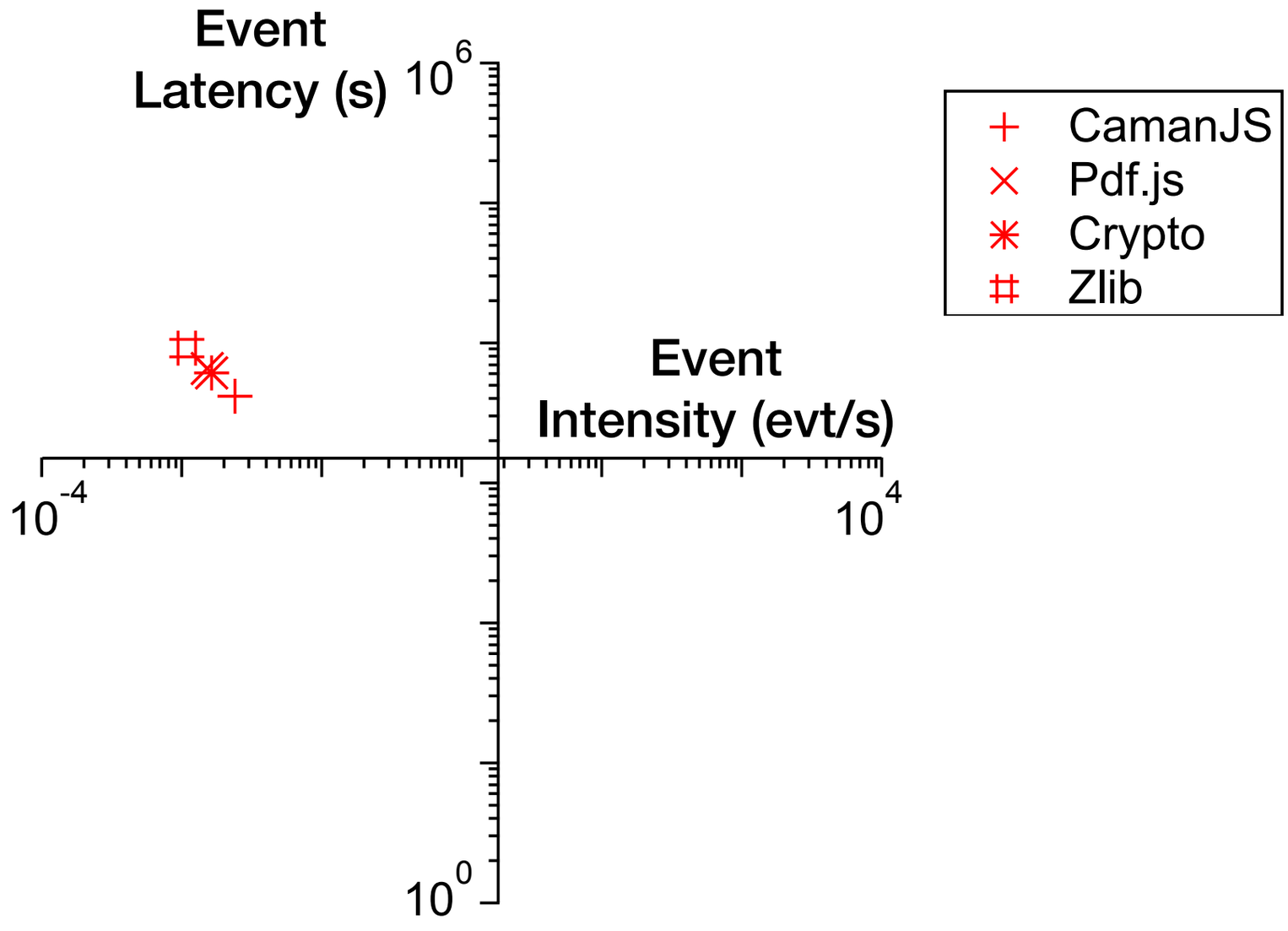

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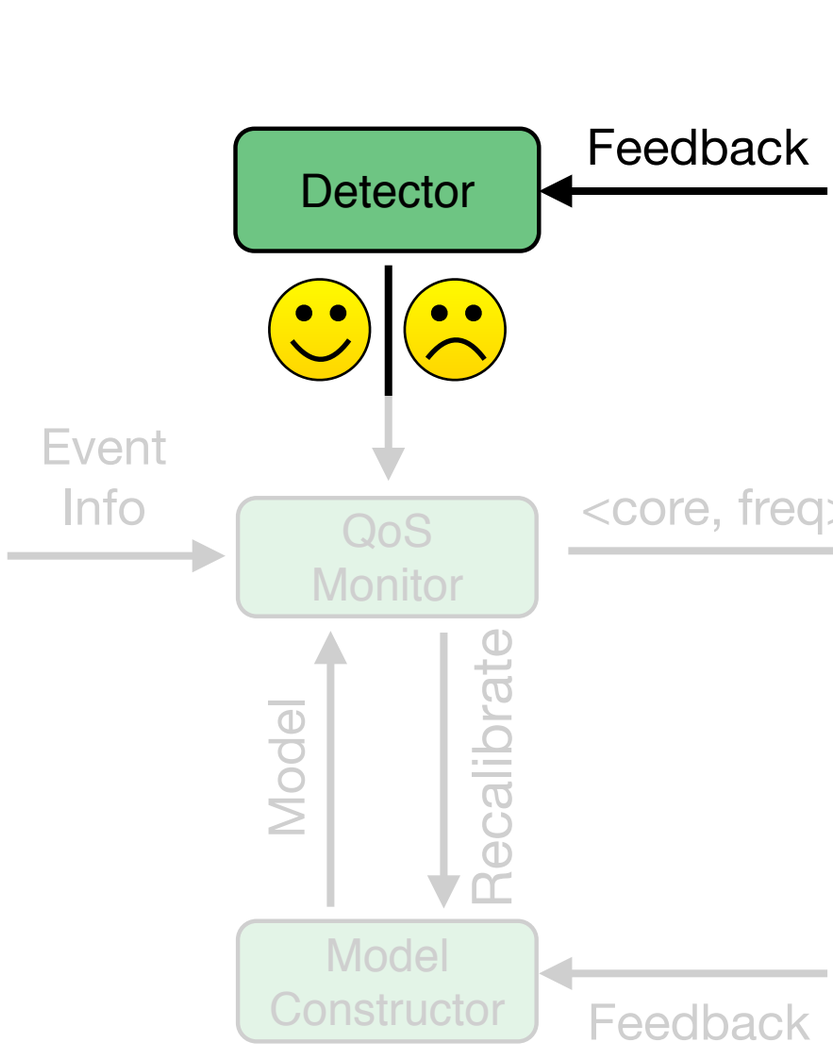

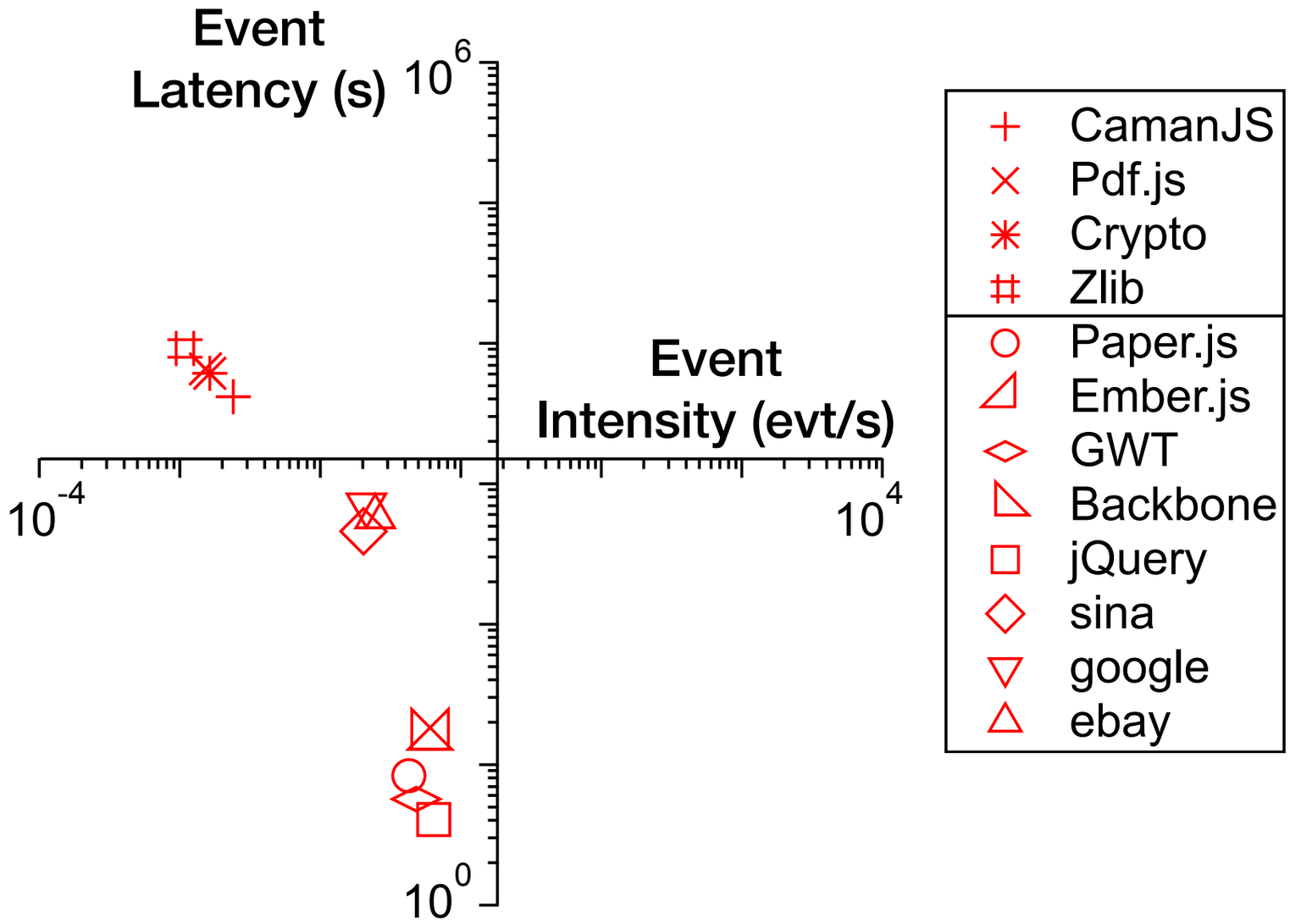

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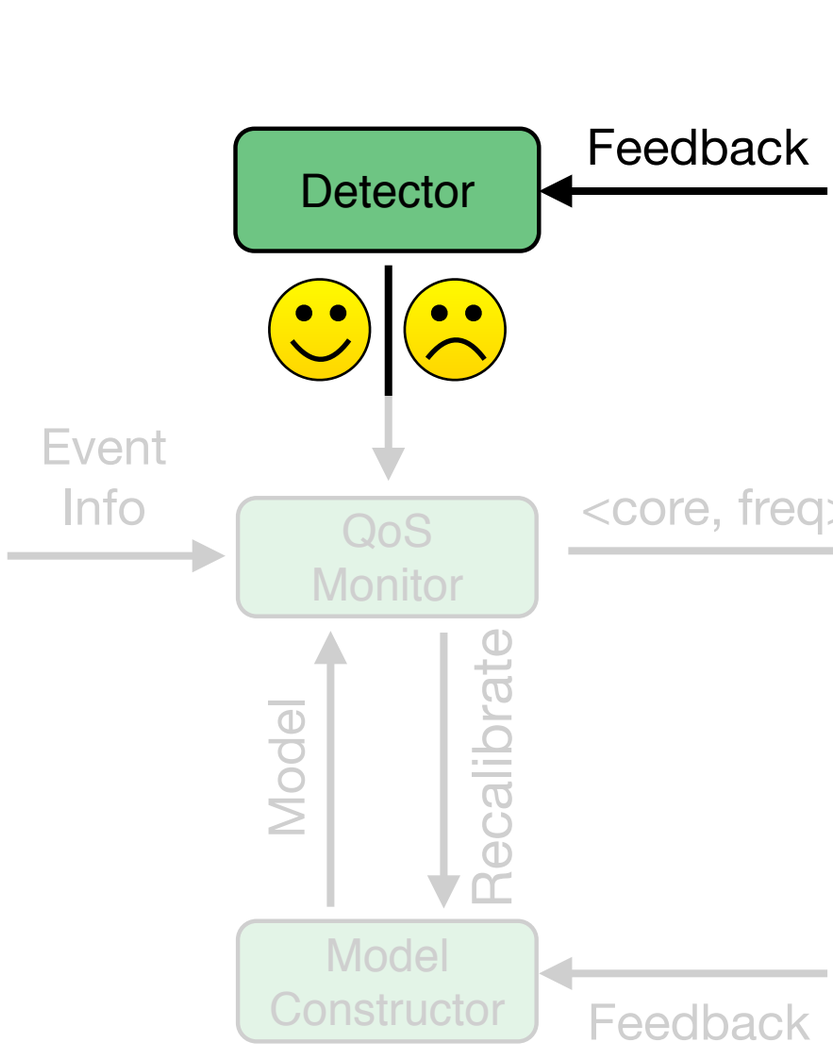

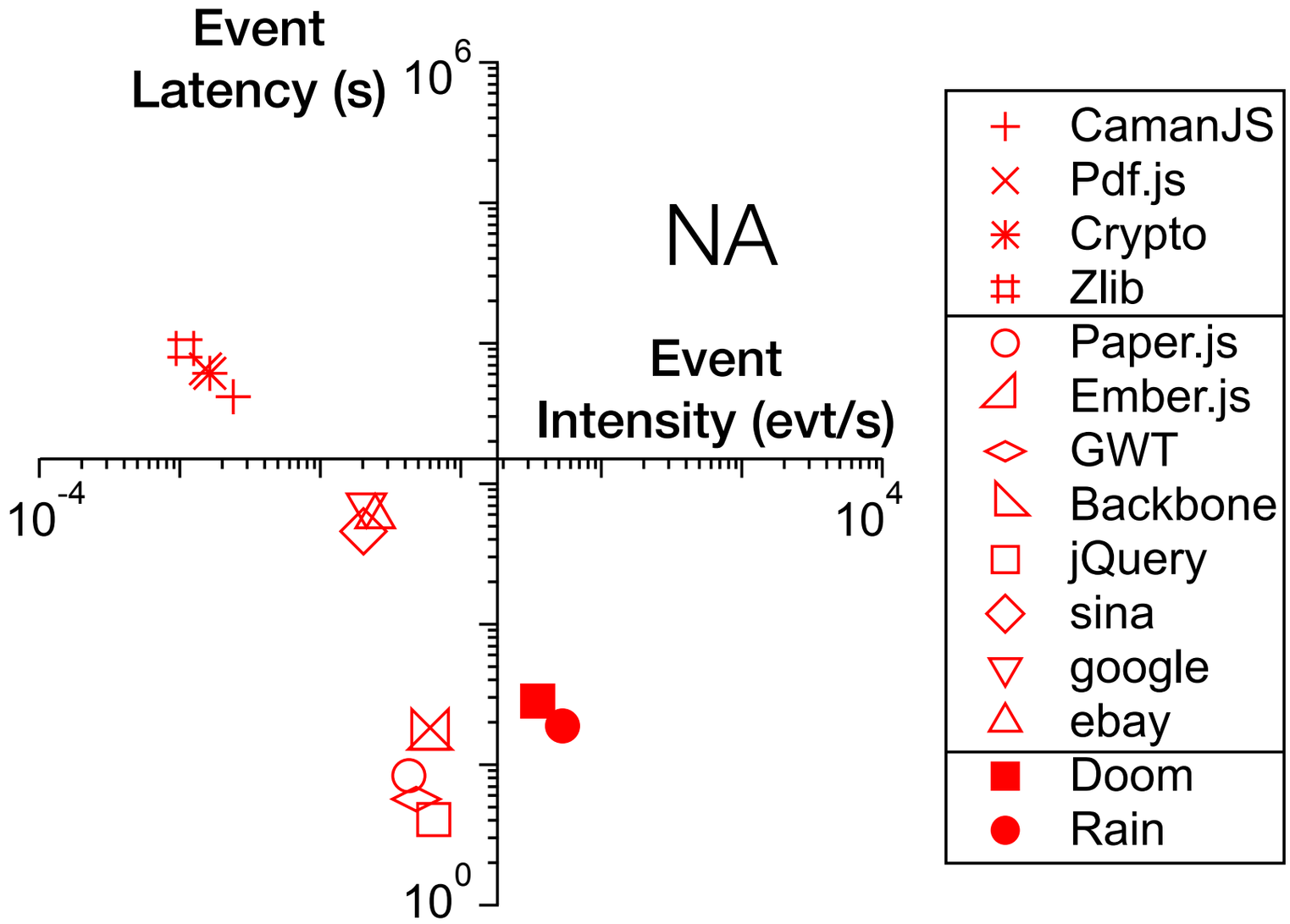

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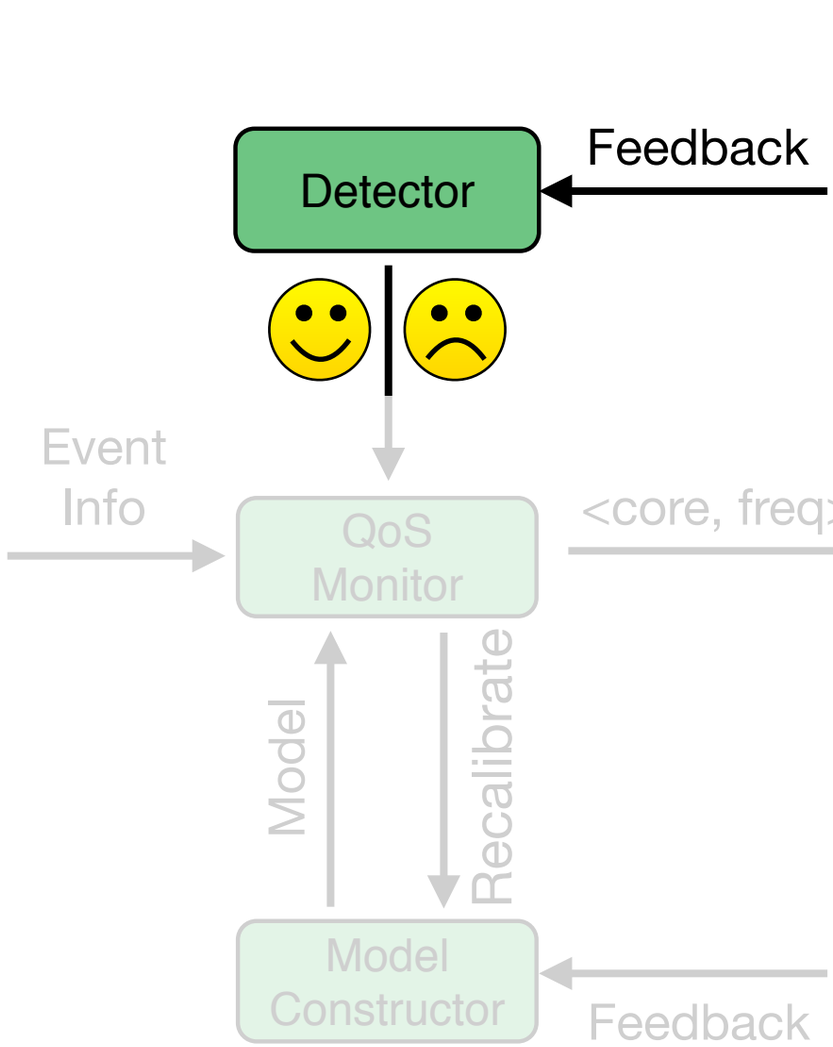
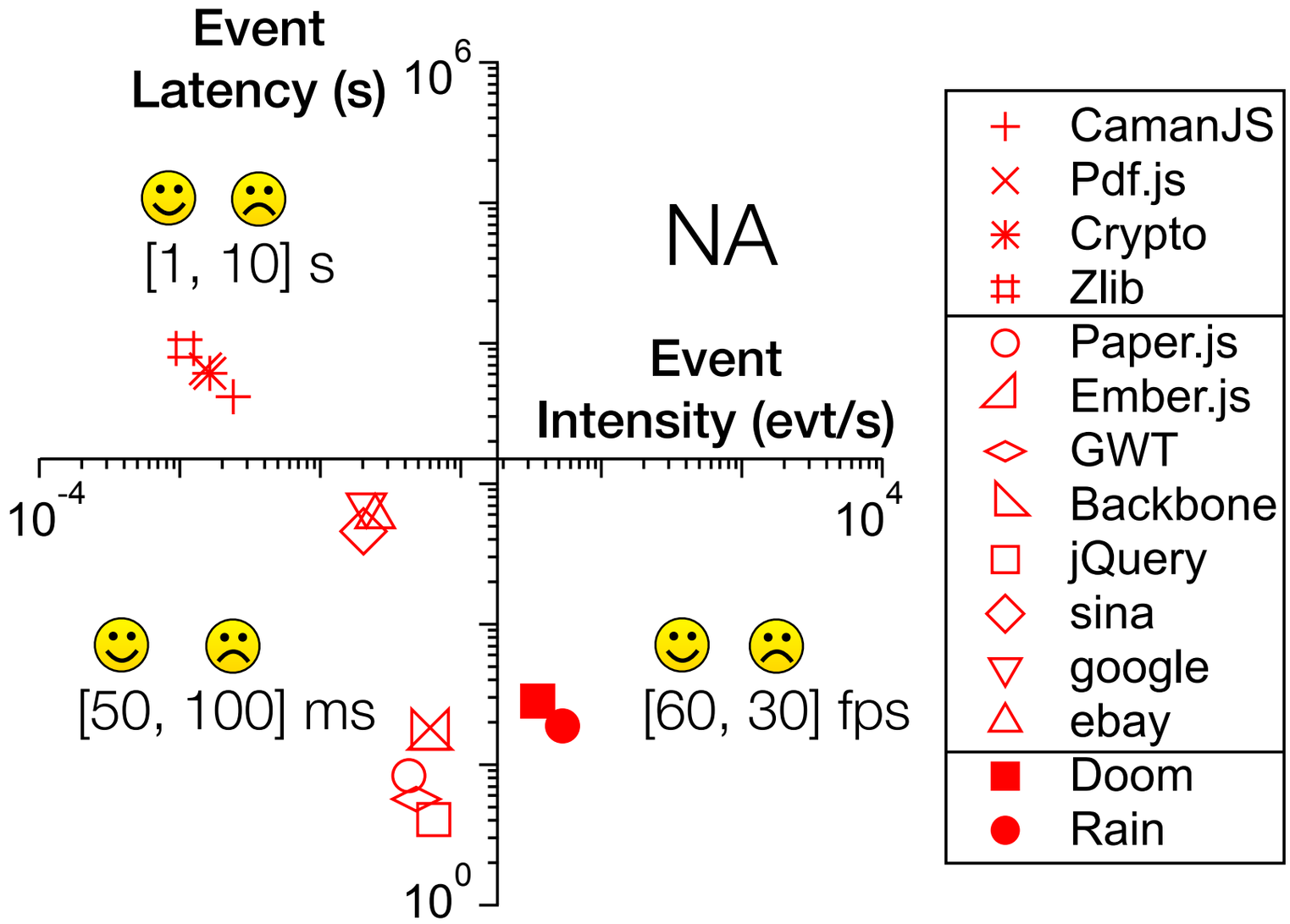
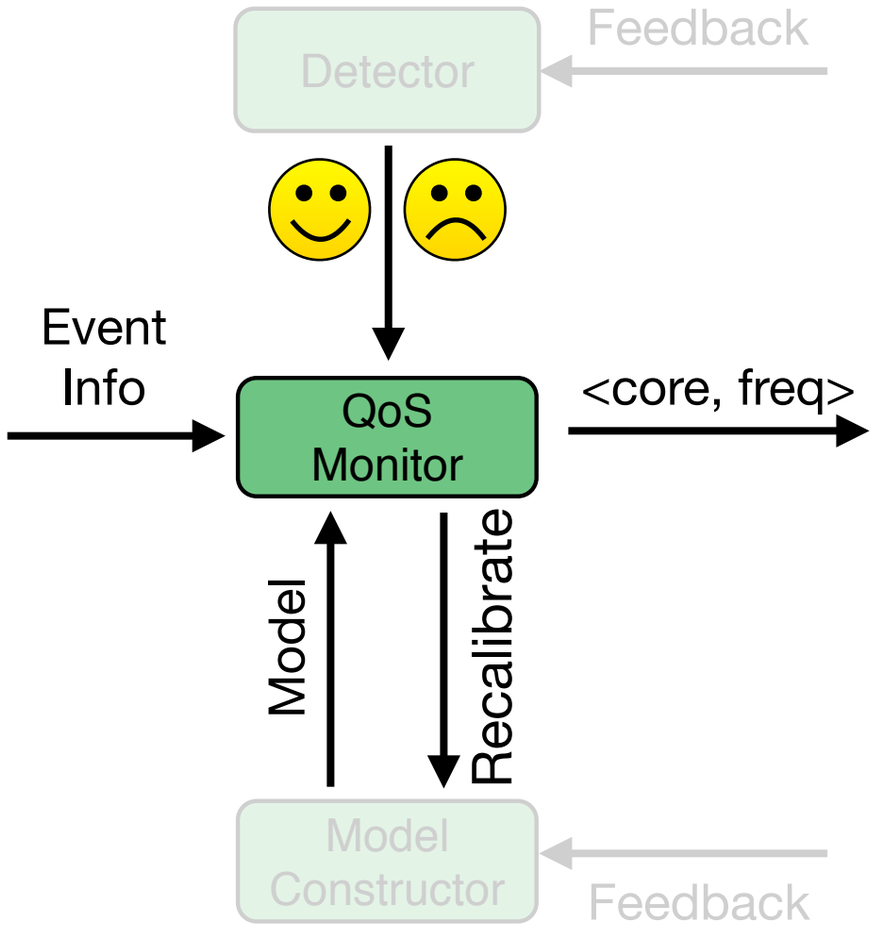




How the QoS Monitor Works

- **Goal**: Predict the <core, frequency> for the next event



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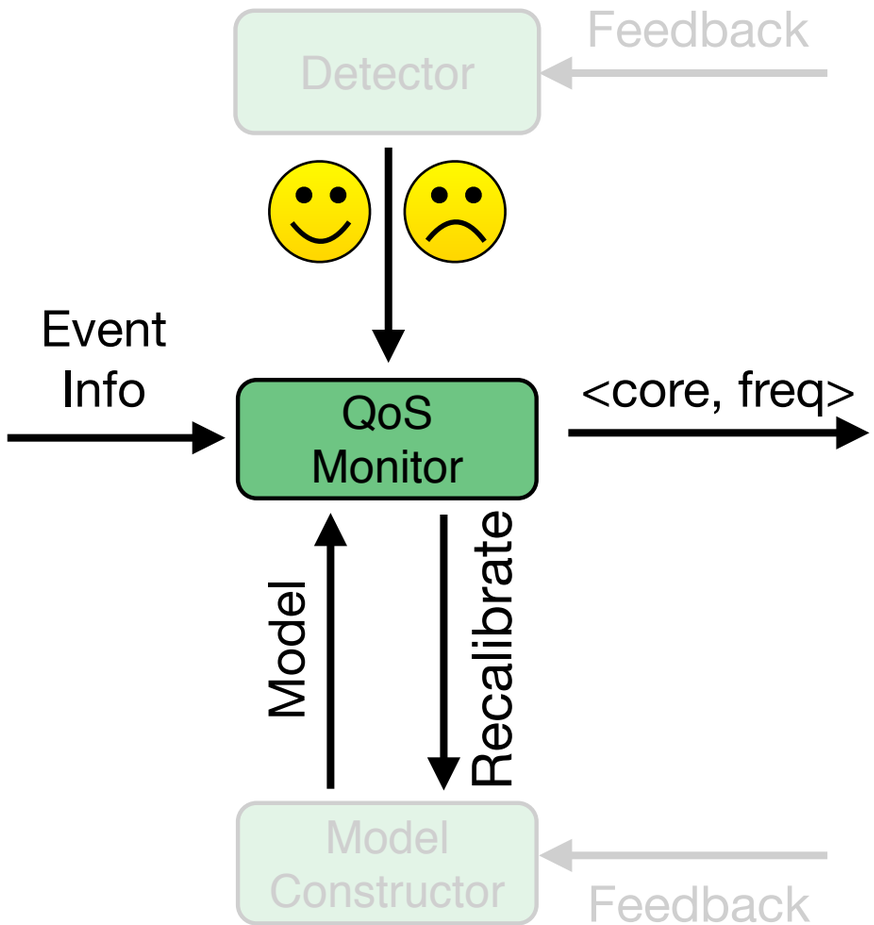

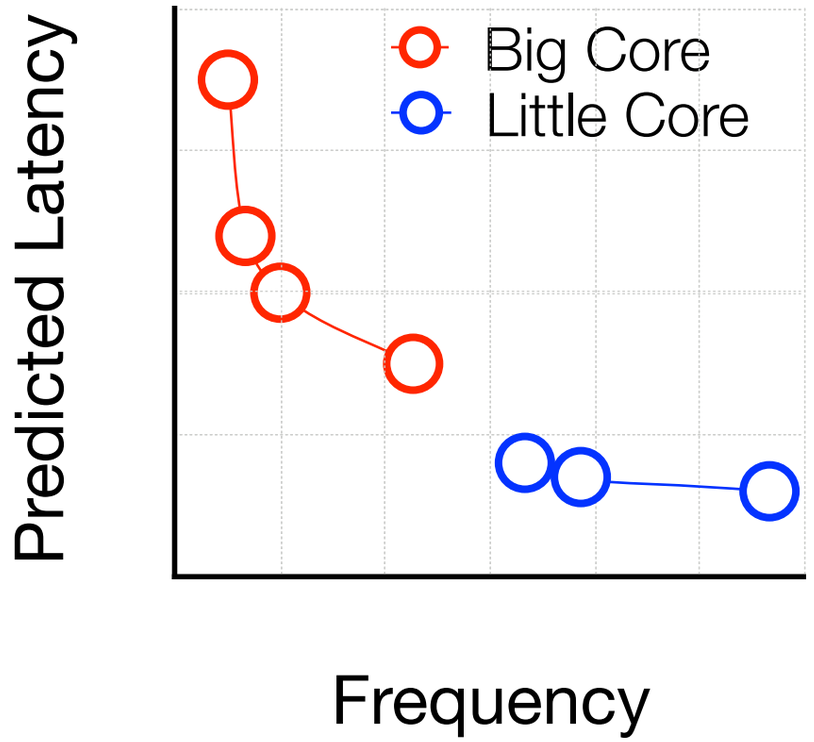

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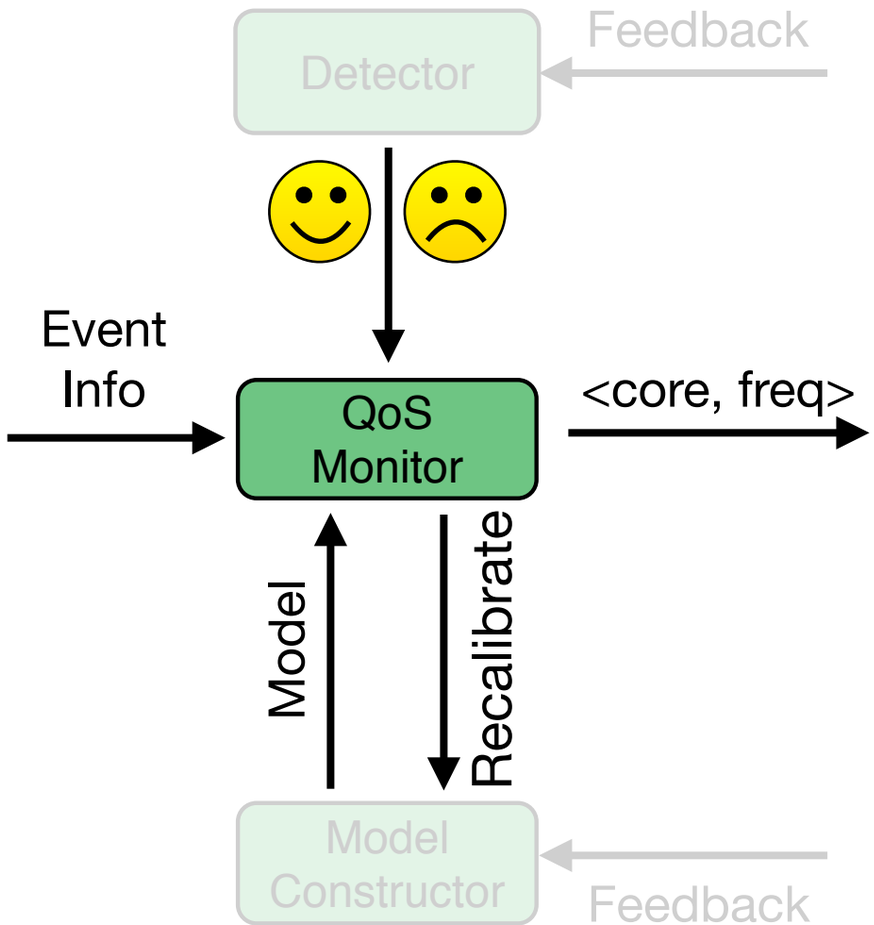

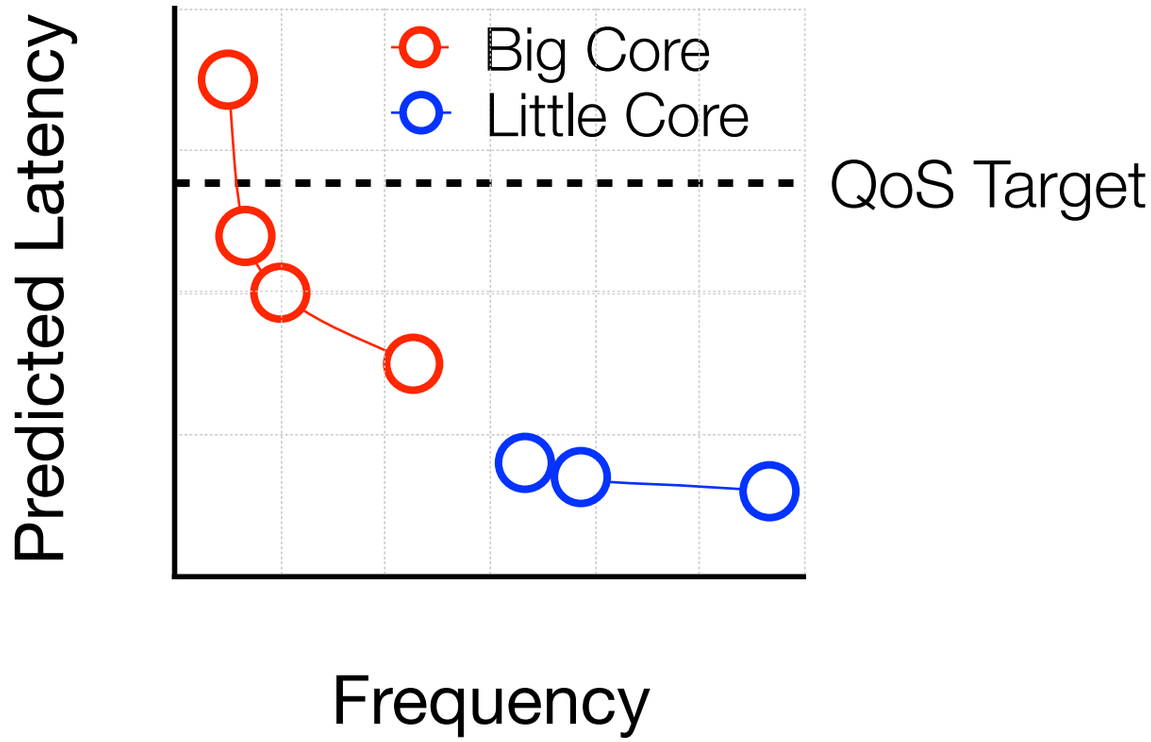

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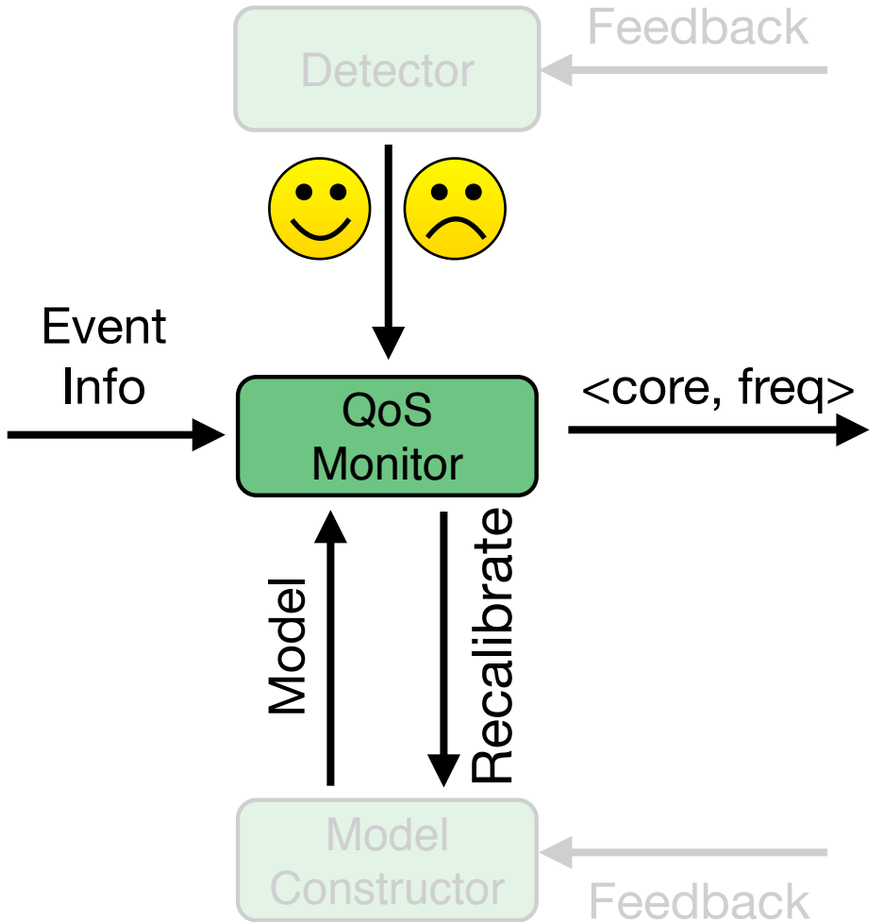

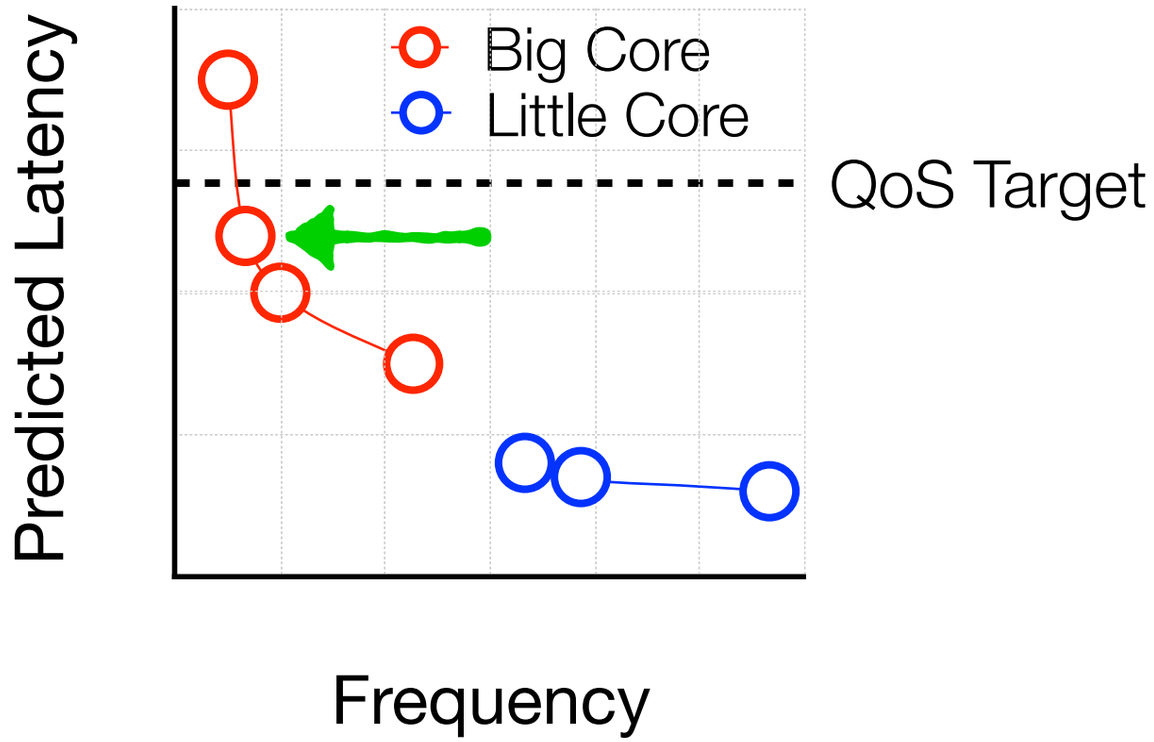

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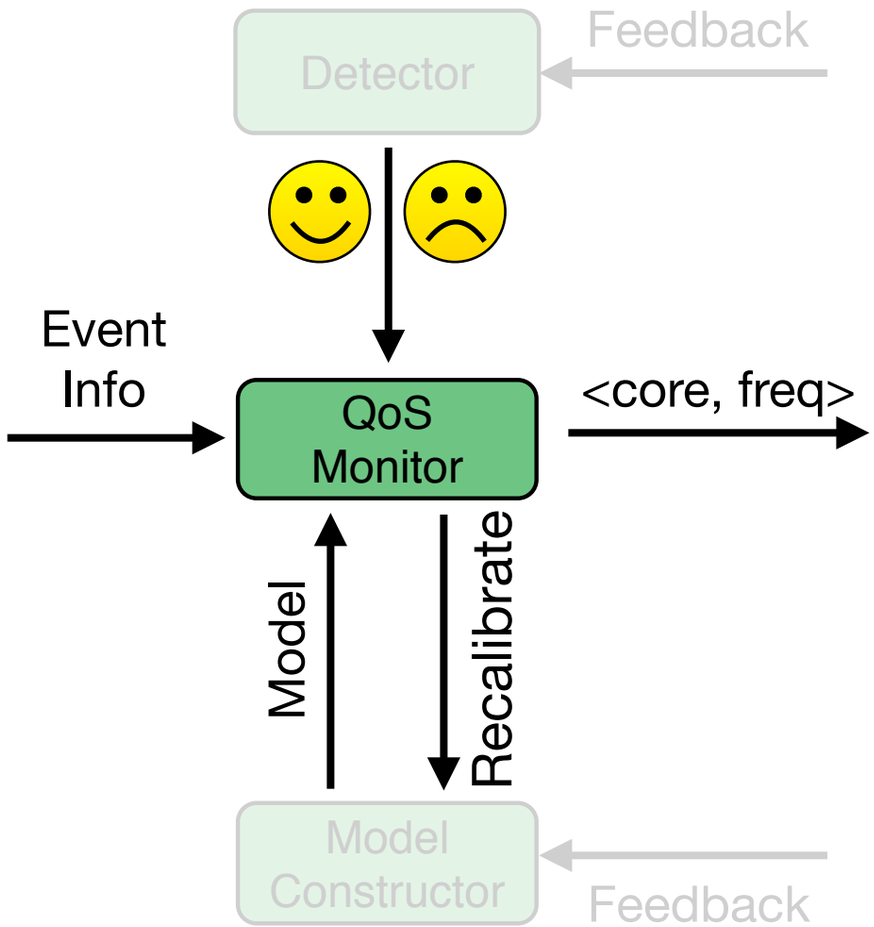
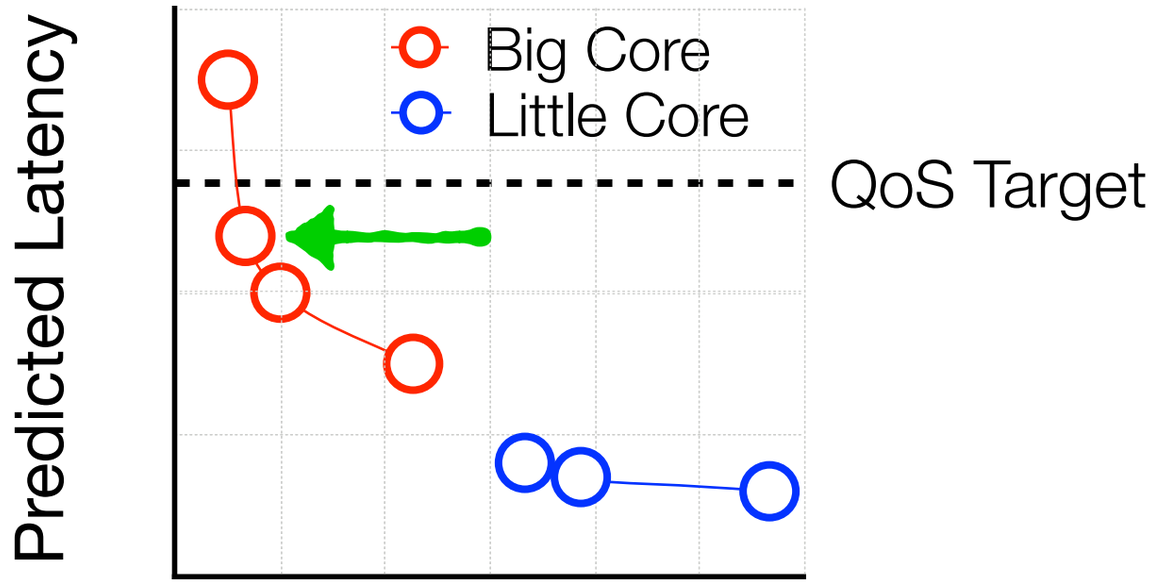
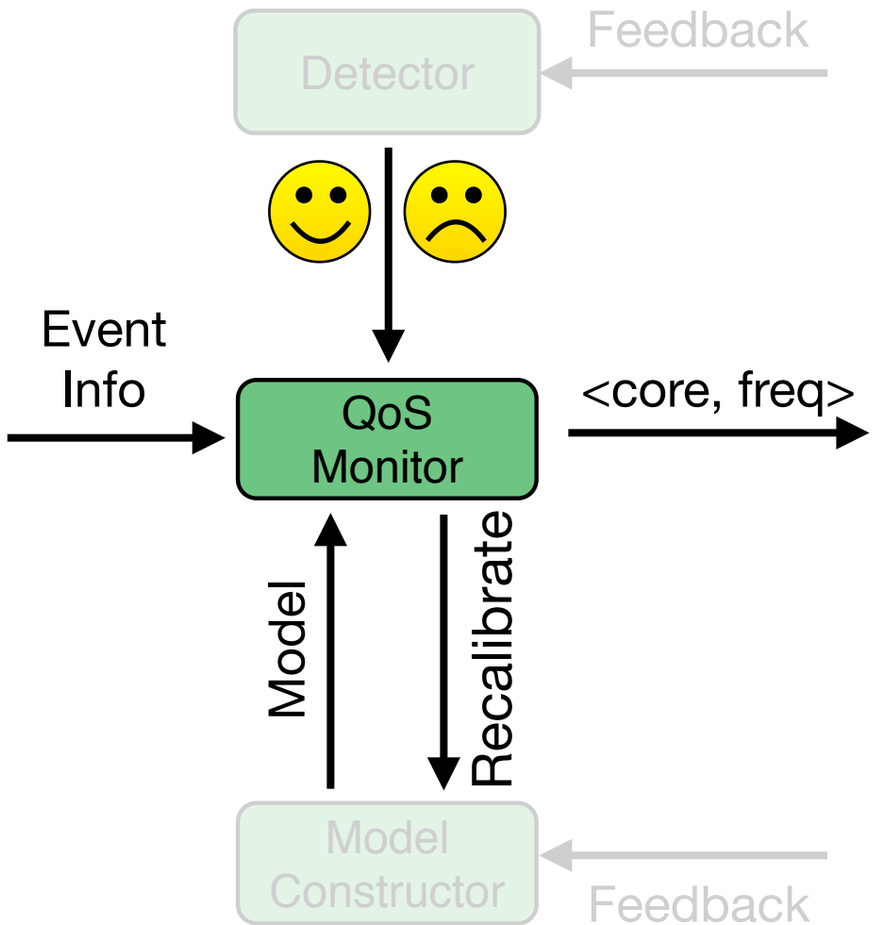


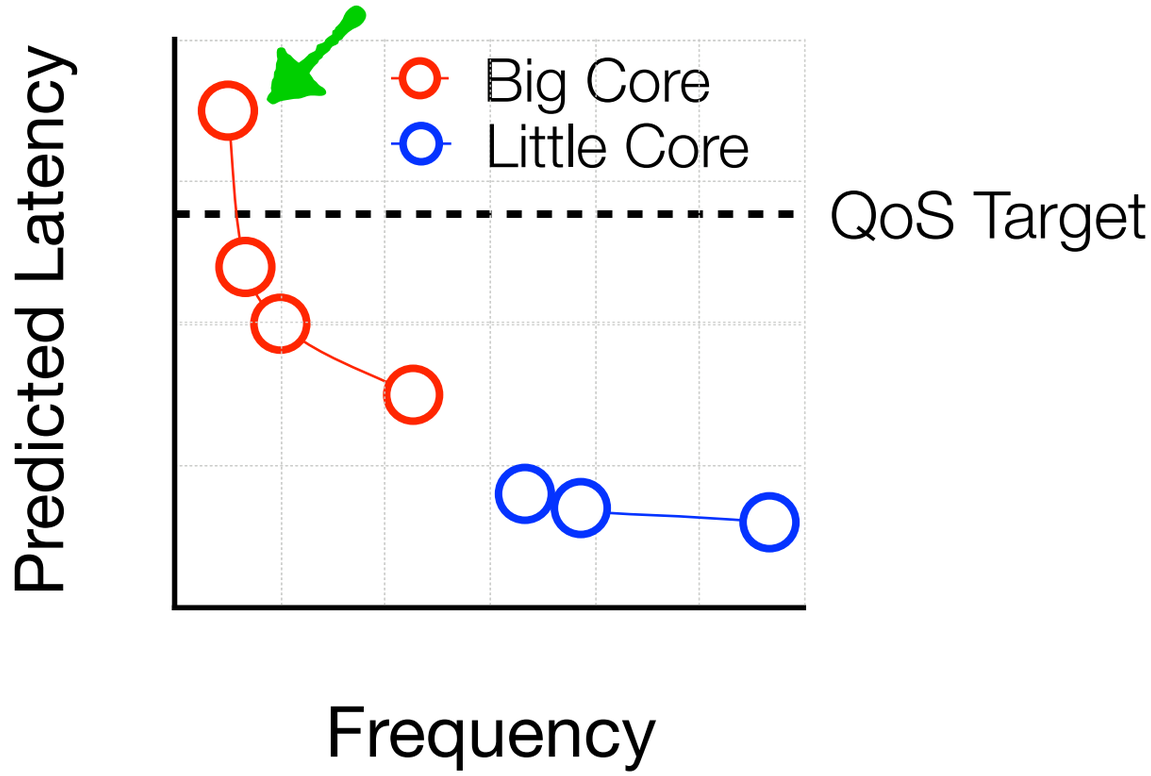


- Scheduling overhead (~120 us):
  - Core migration
  - Frequency switching

How the QoS Monitor Works

- **Goal**: Predict the <core, frequency> for the next event





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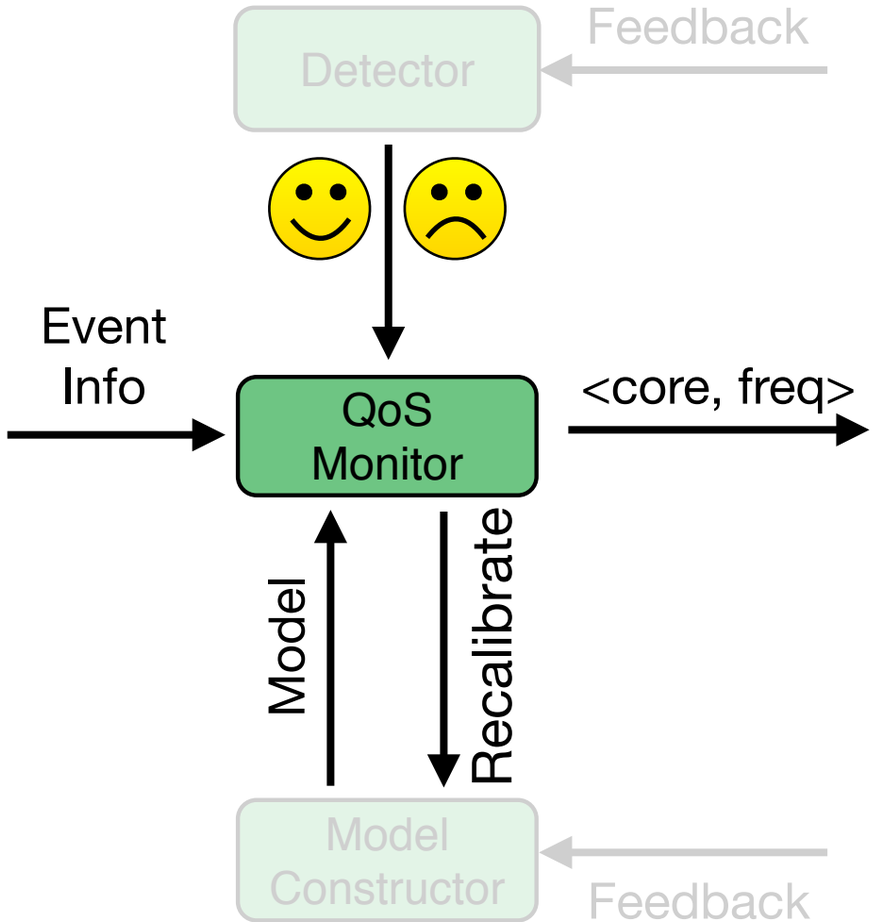

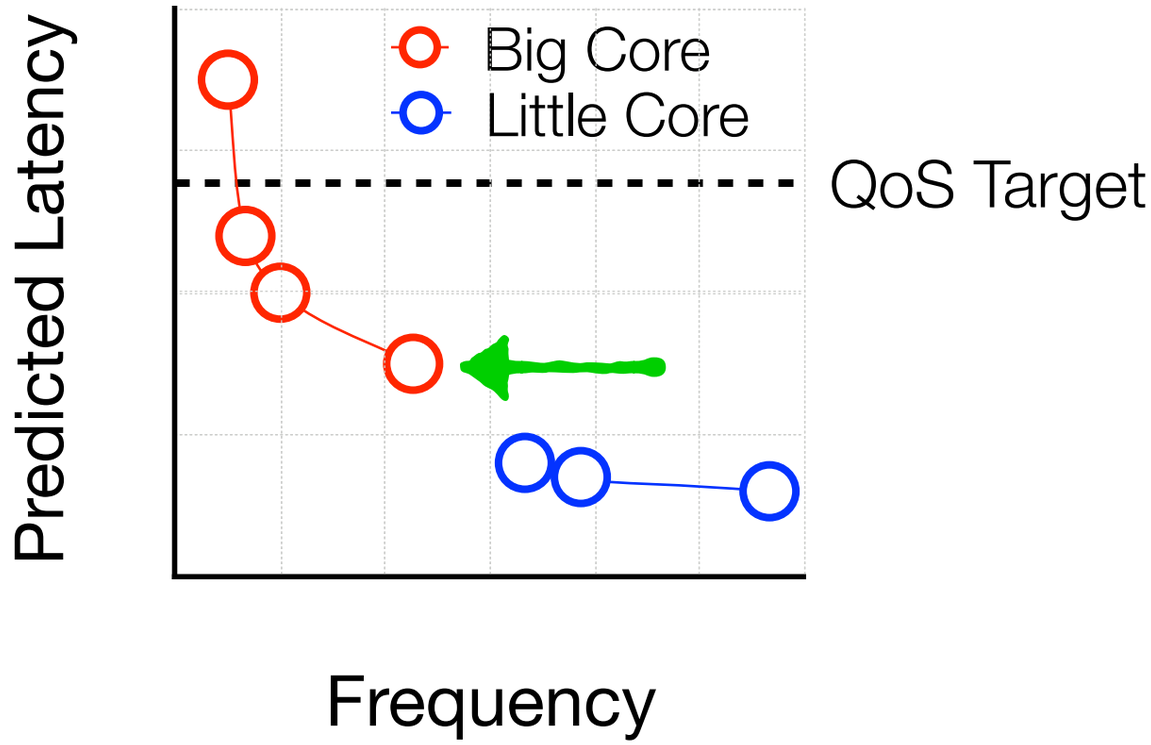

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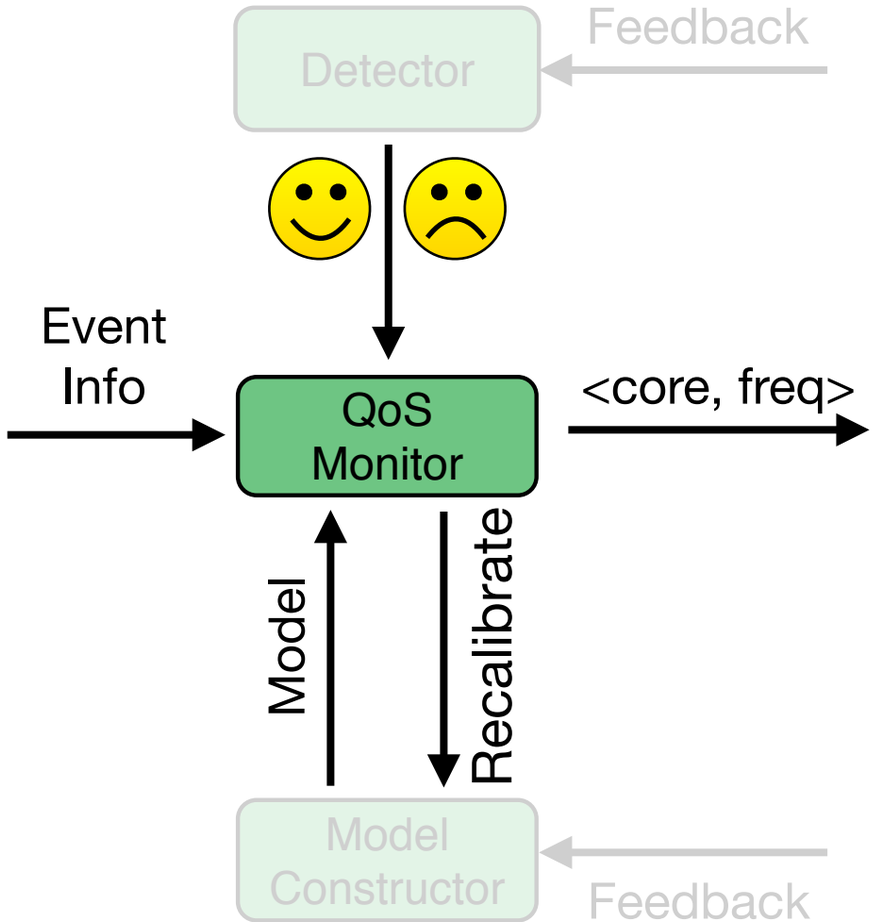

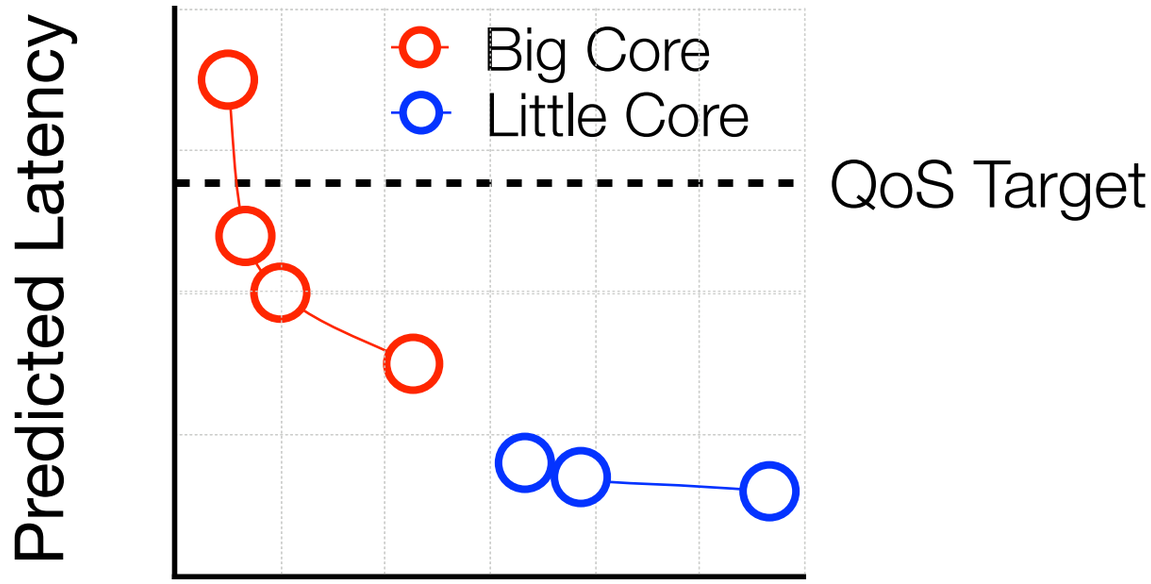

- Fine-tune the execution upon over-prediction or under-prediction

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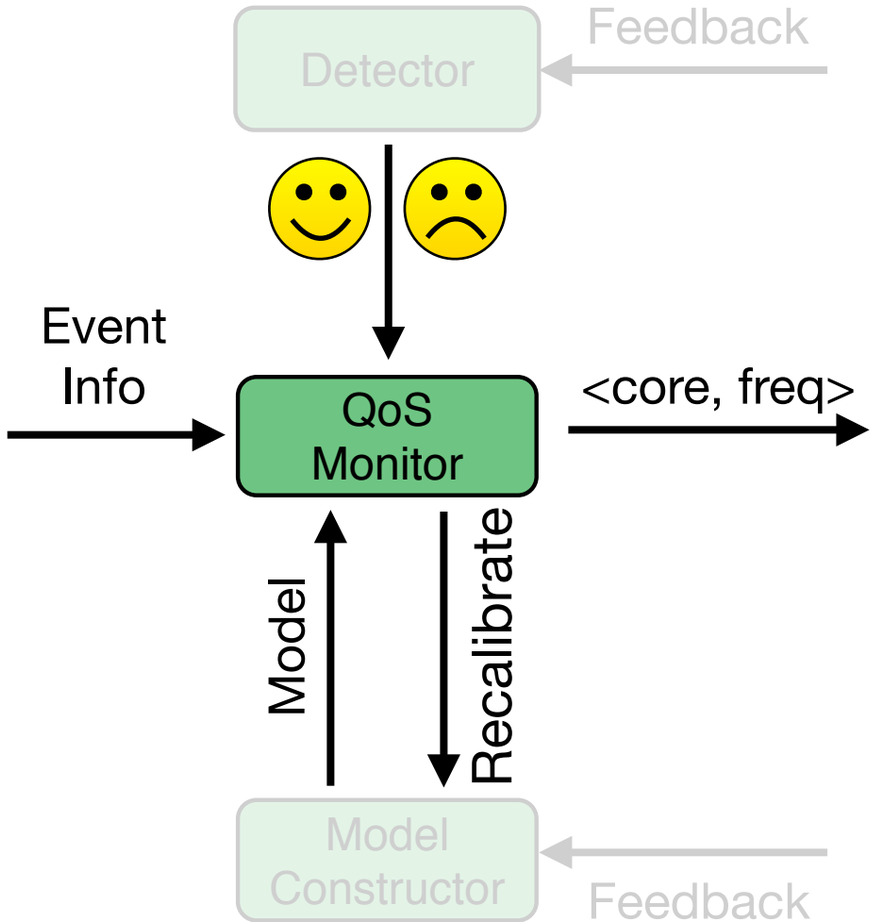

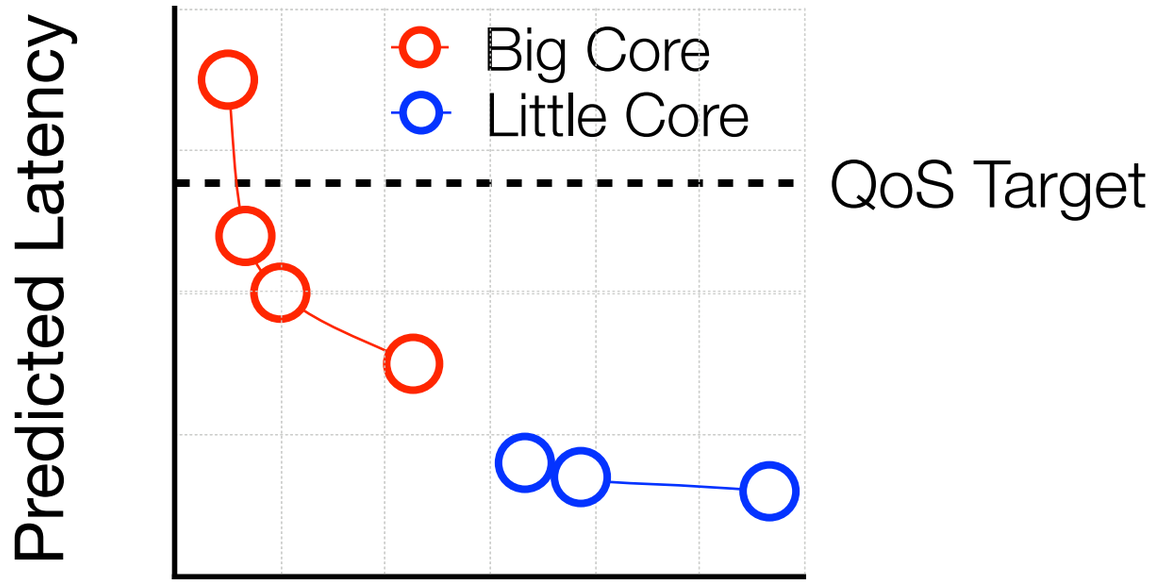

- Fine-tune the execution upon over-prediction or under-prediction
- Recalibrate if it mispredicts too often

Evaluation Methodology

- Implemented inside Google Chromium Web browser

- Representative hardware platform
  - Exynos 5410 SoC (A15 + A7)

Evaluation Methodology

- Baseline Mechanisms
  - Highest performance (**Perf**) — Standard to guarantee responsiveness
  - Minimal energy (**Energy**) — Minimize energy consumption
  - Interactive governor (**Interactive**) — Android default
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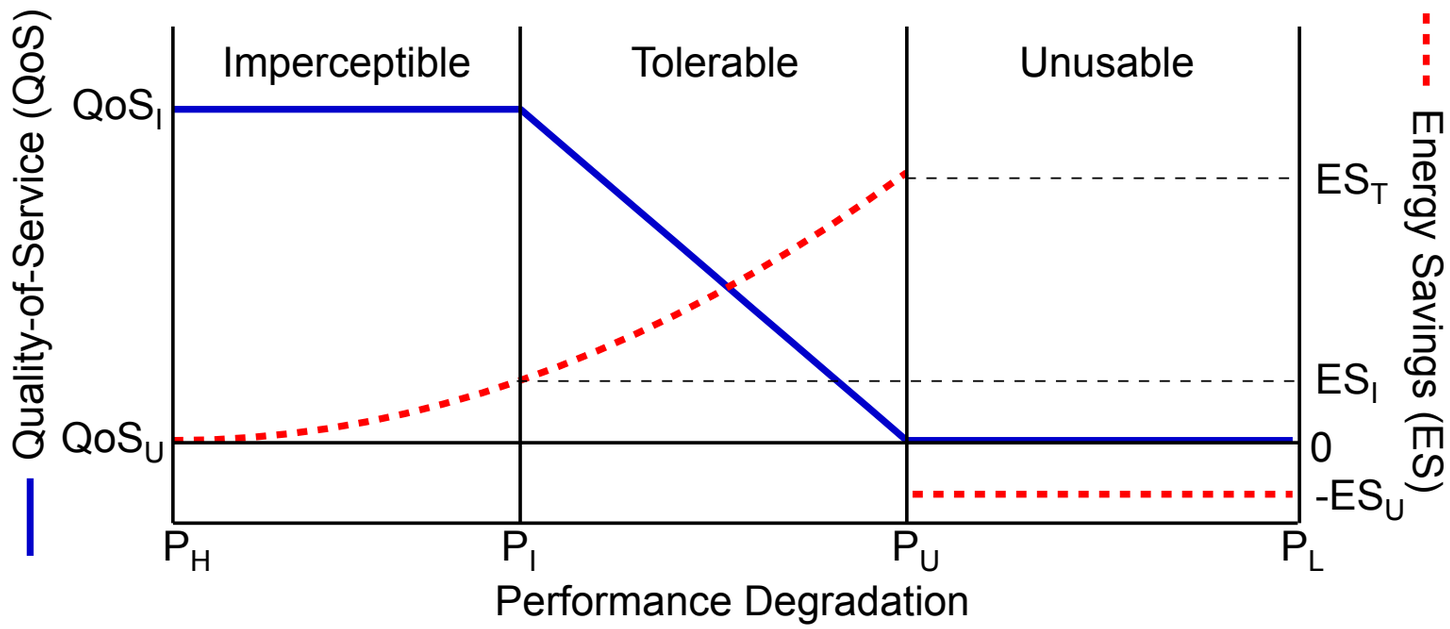

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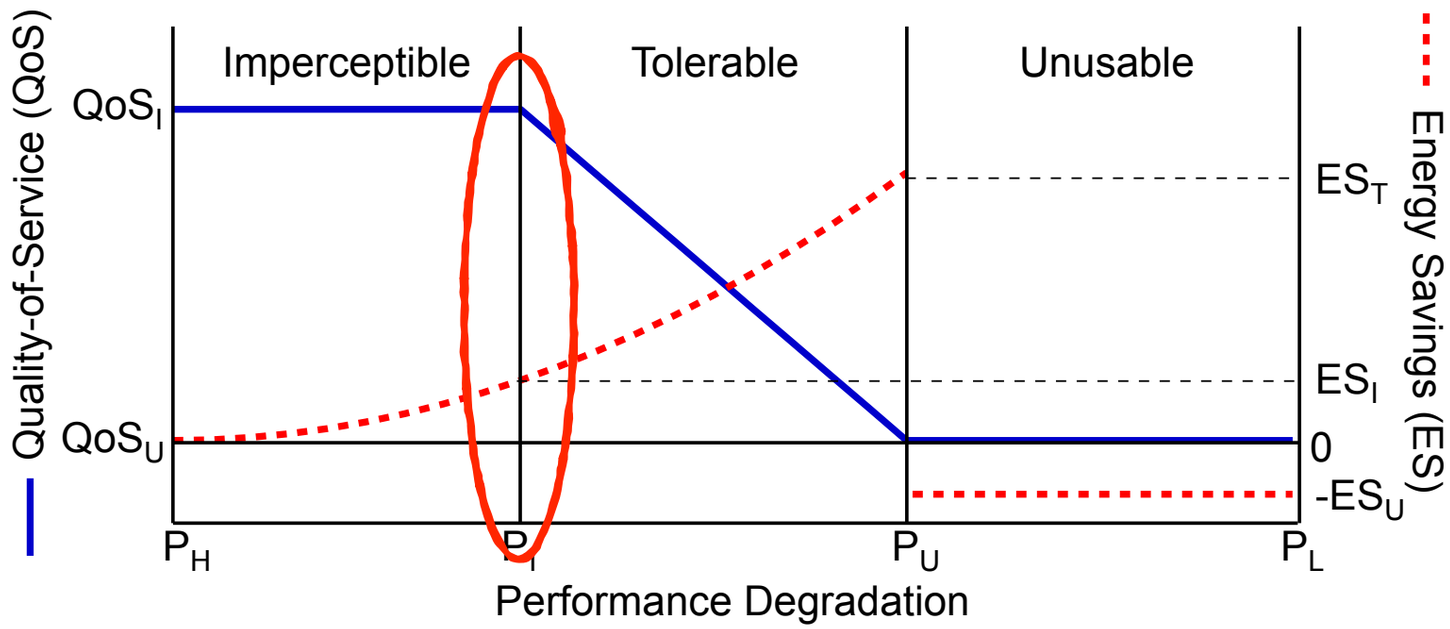
  - Scheduling for imperceptibility



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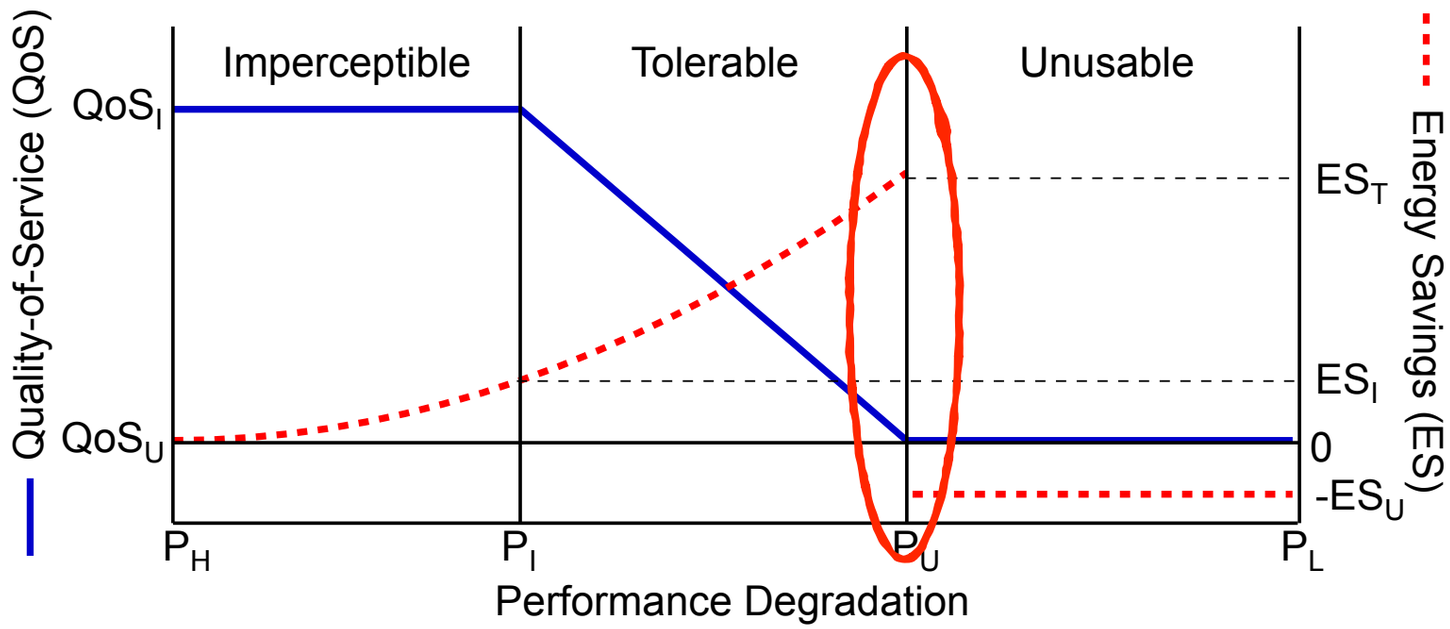

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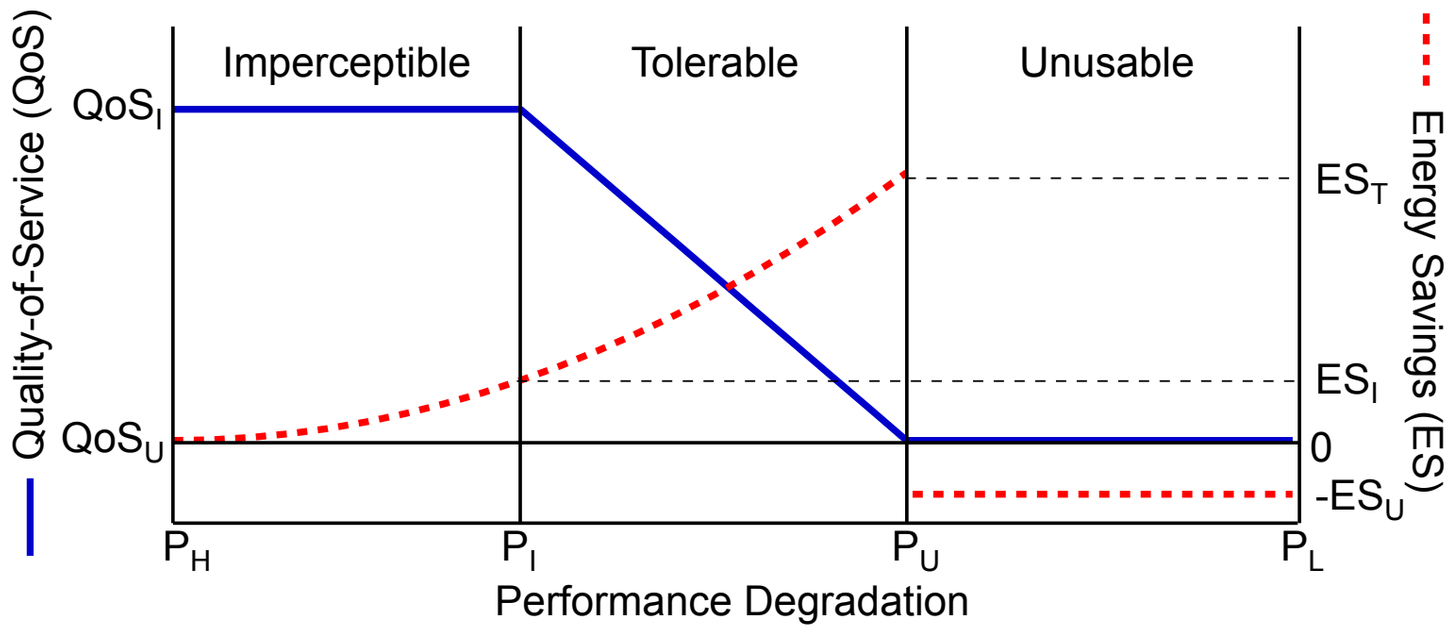
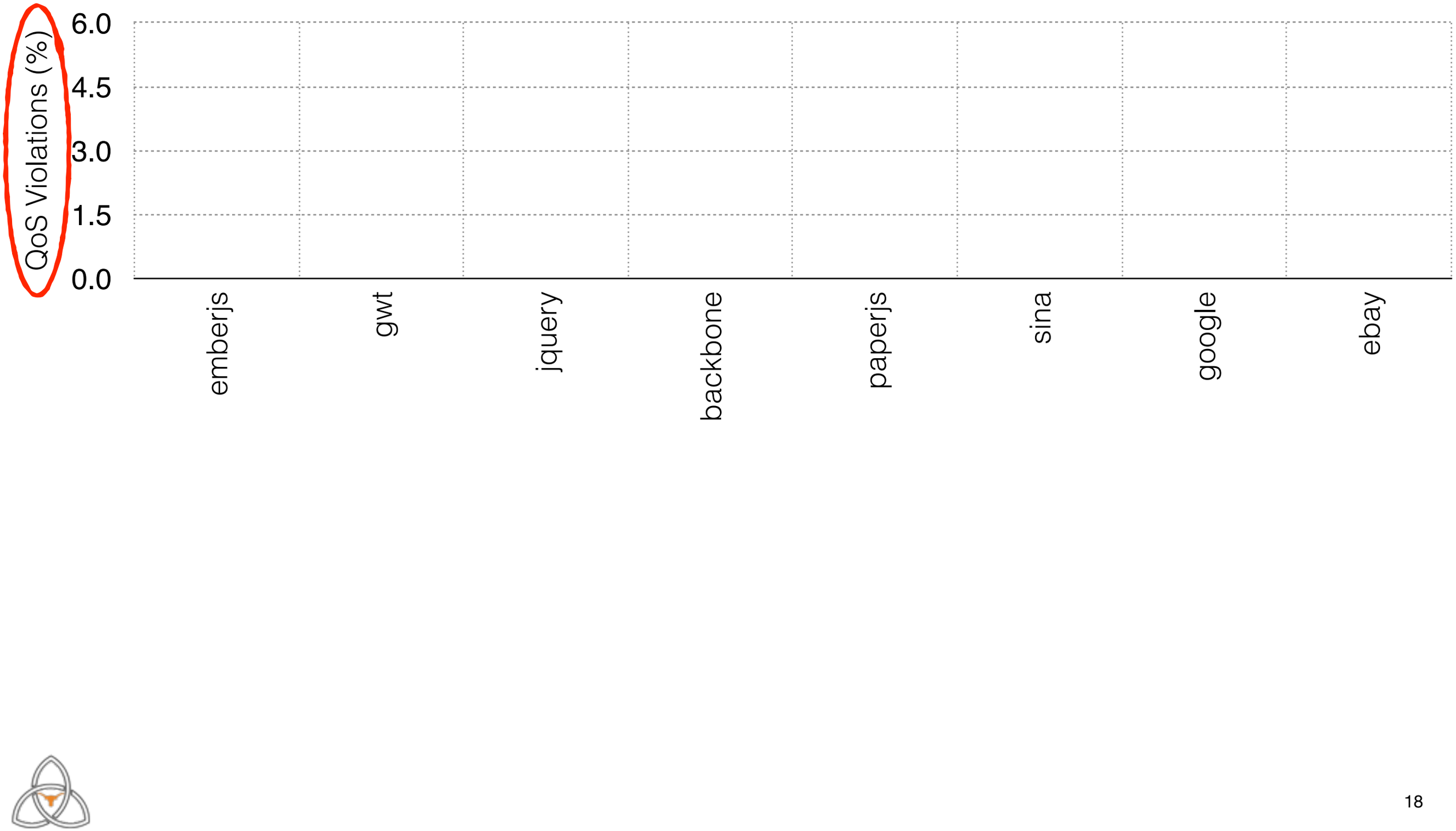


Evaluation Results



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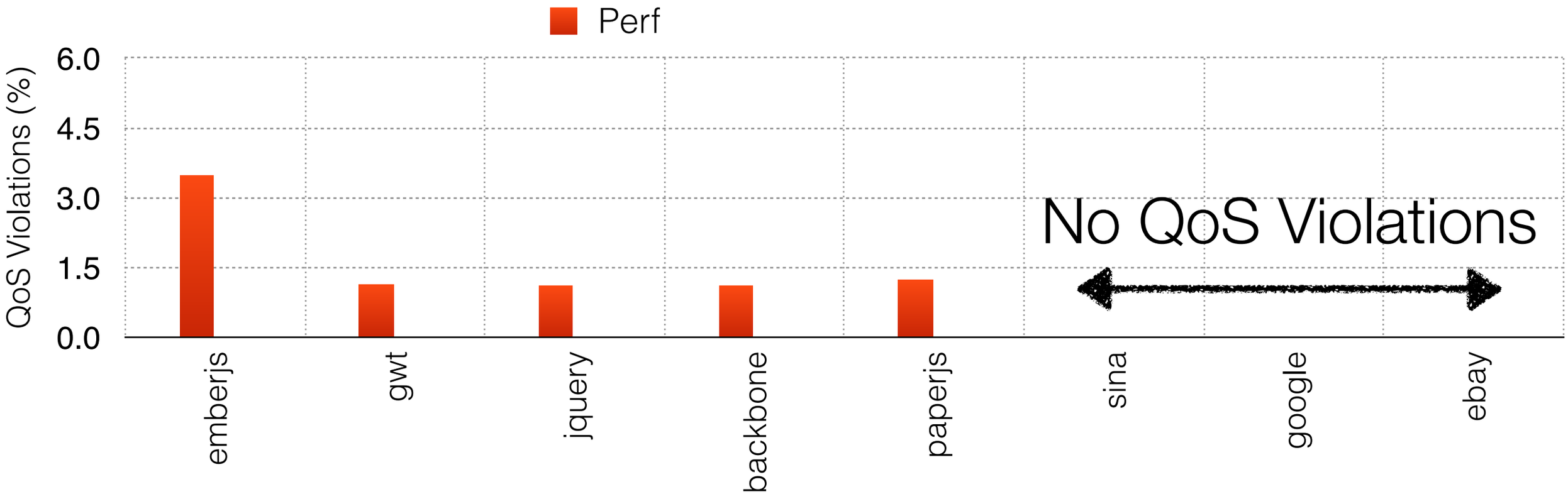

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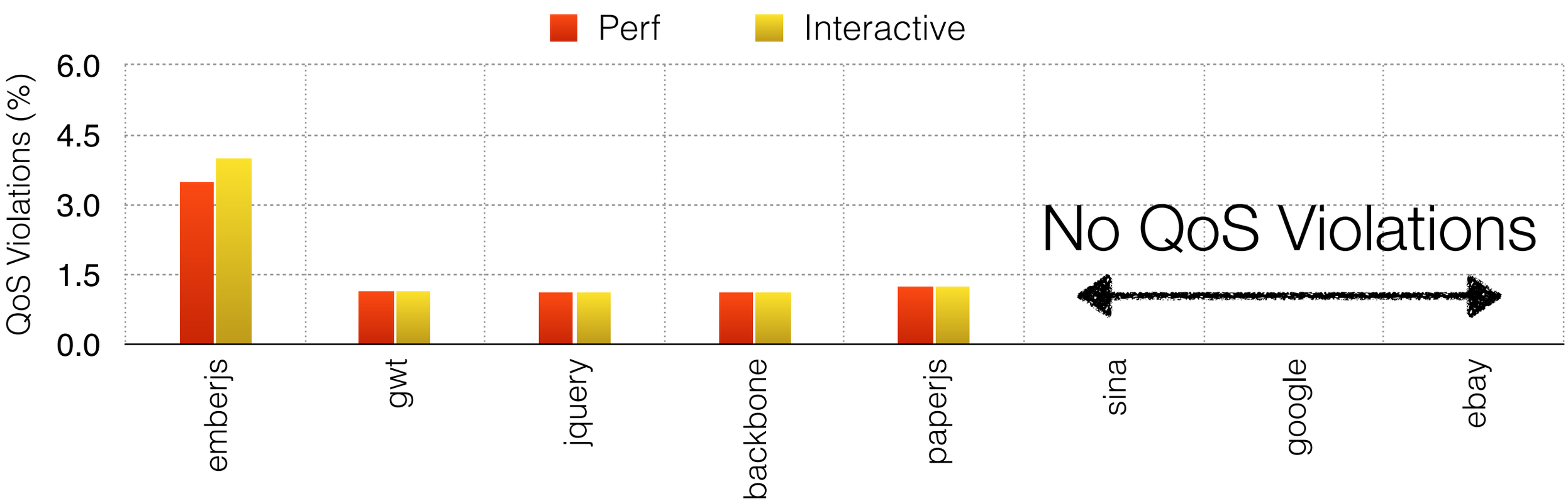

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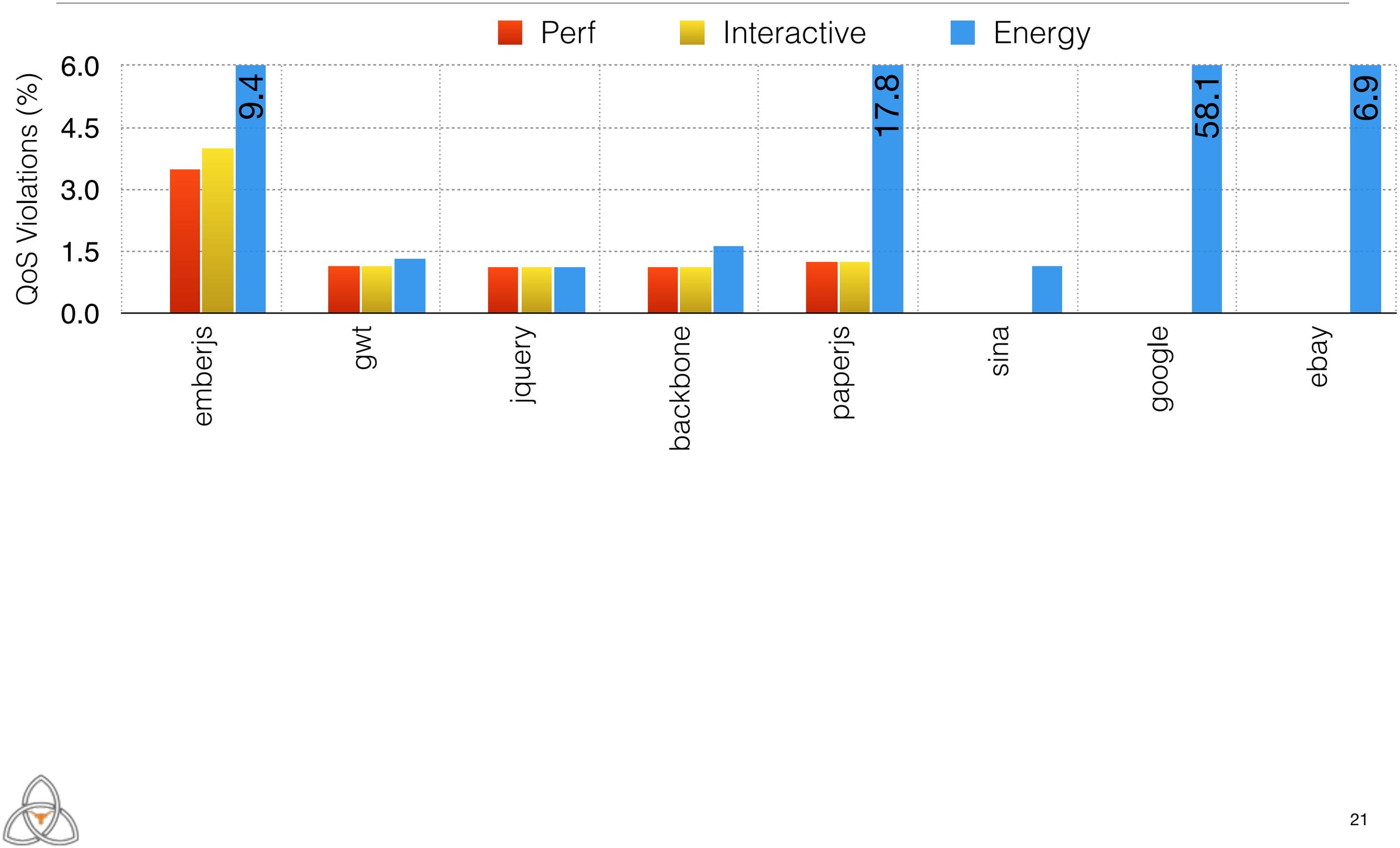

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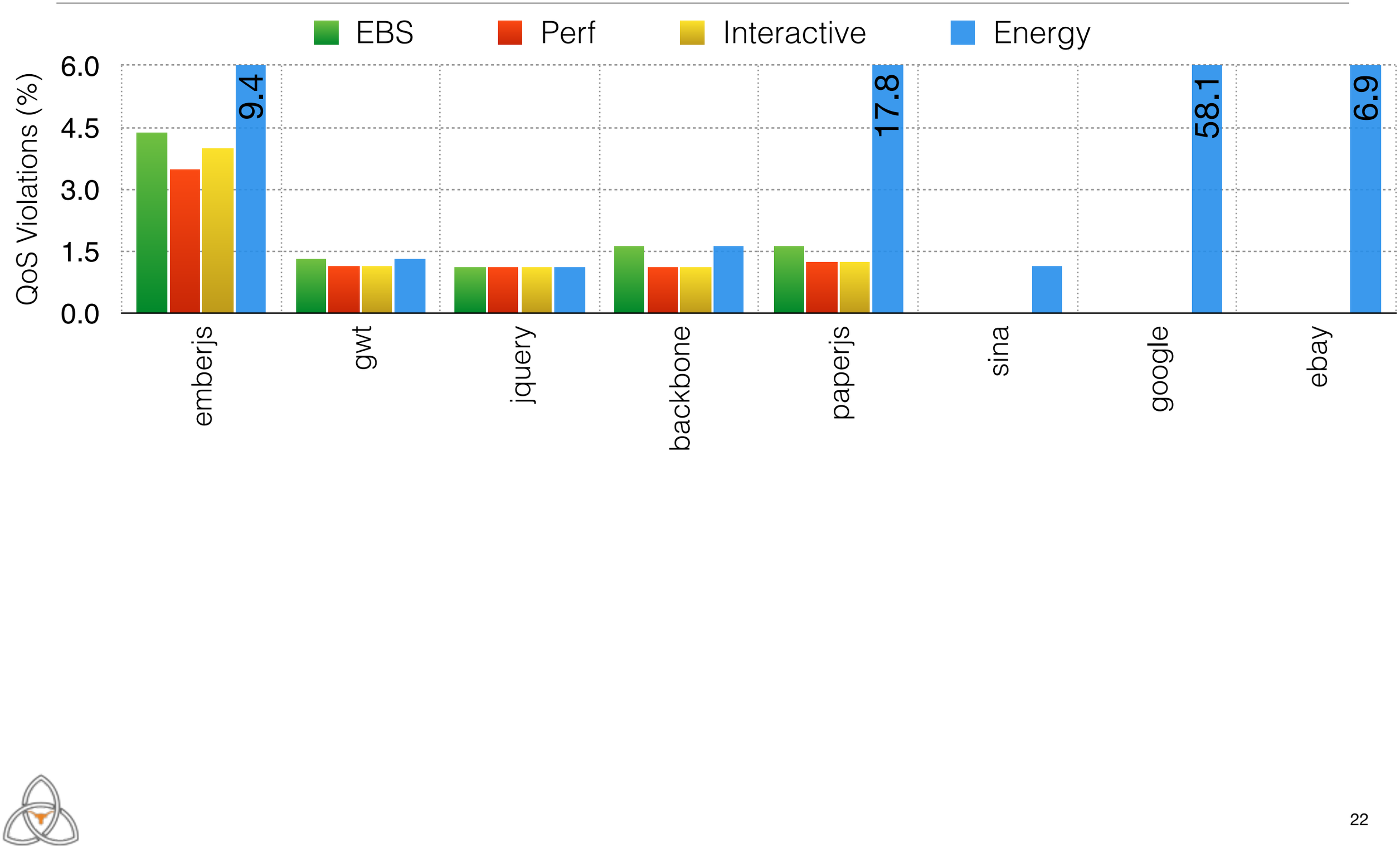

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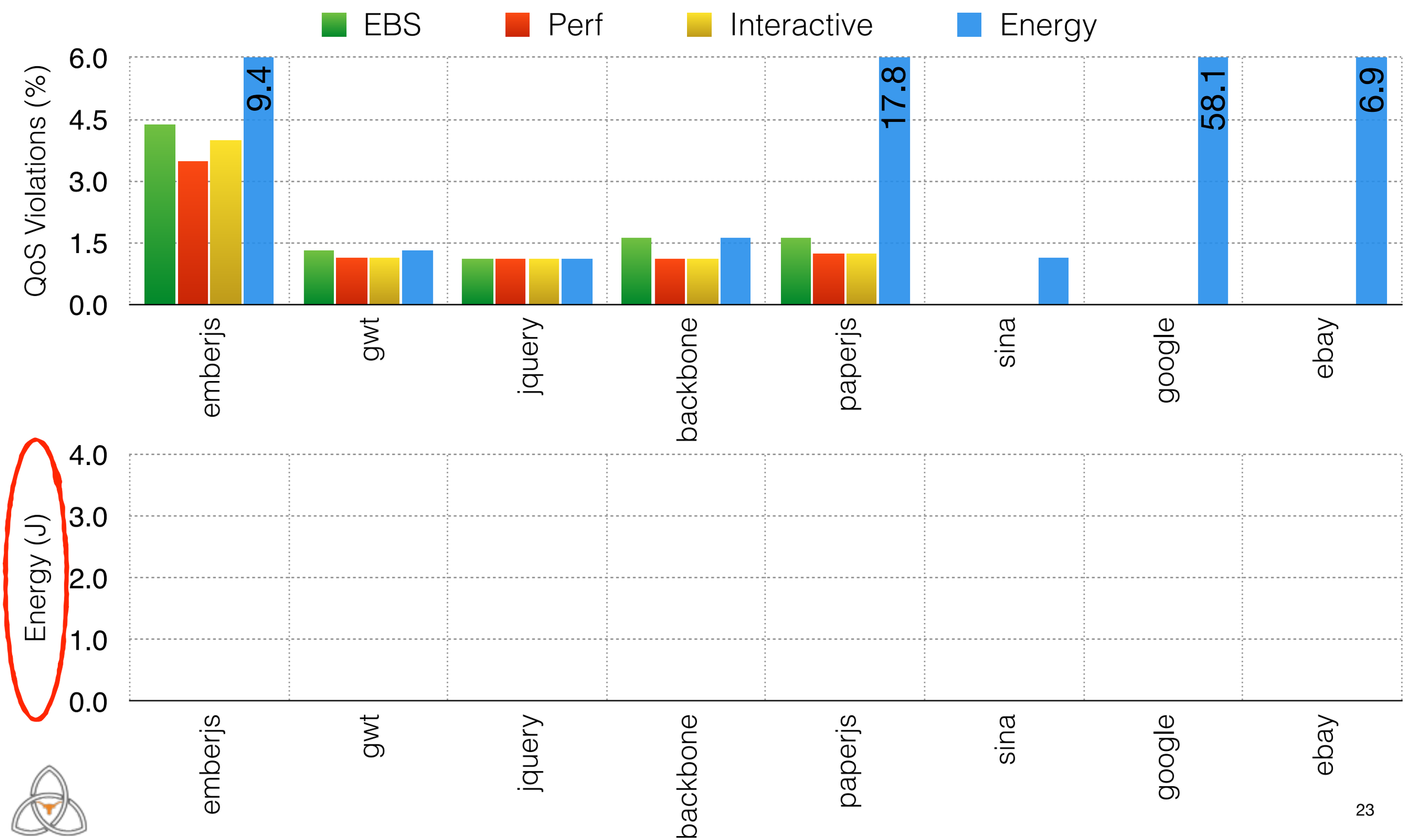

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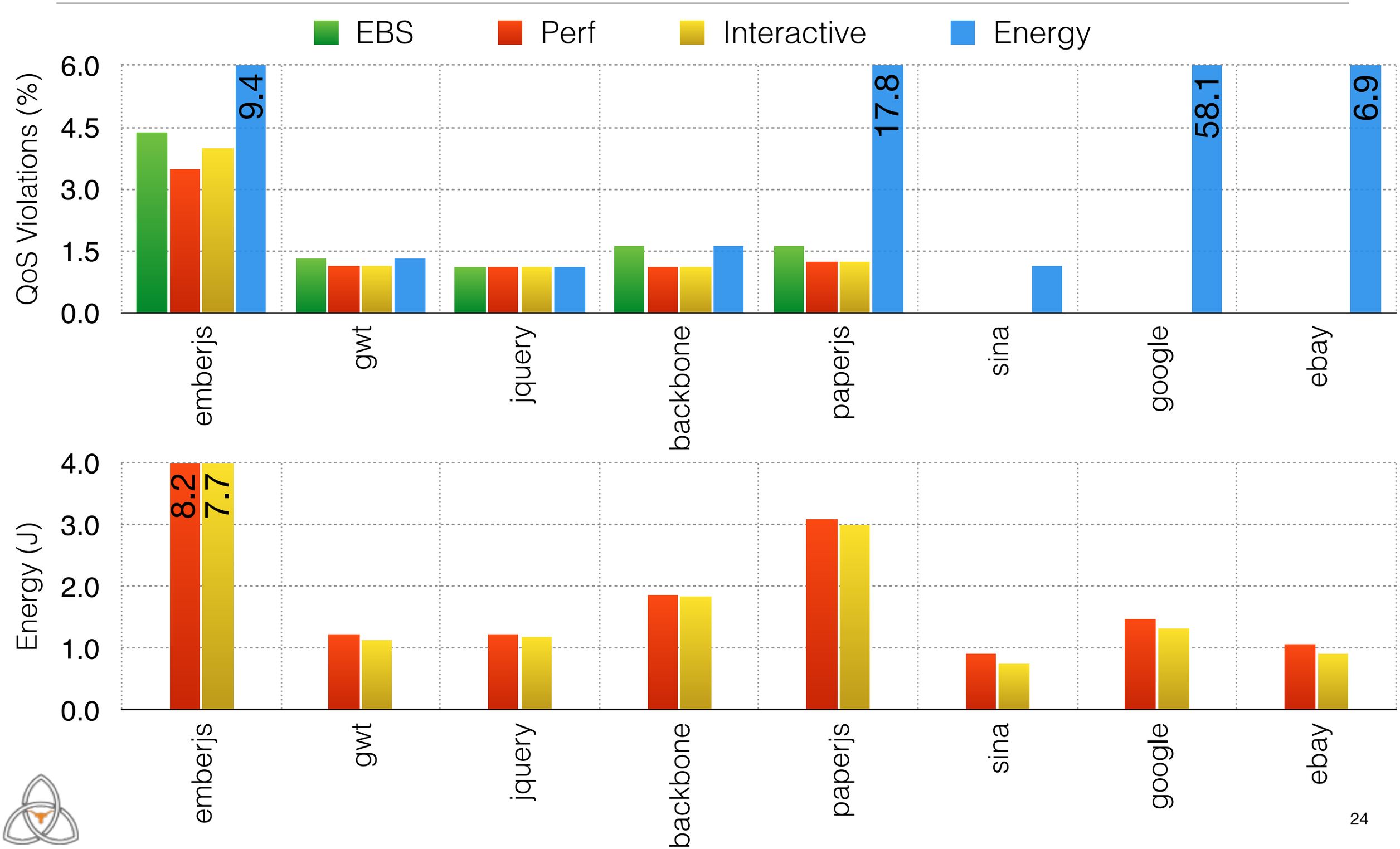

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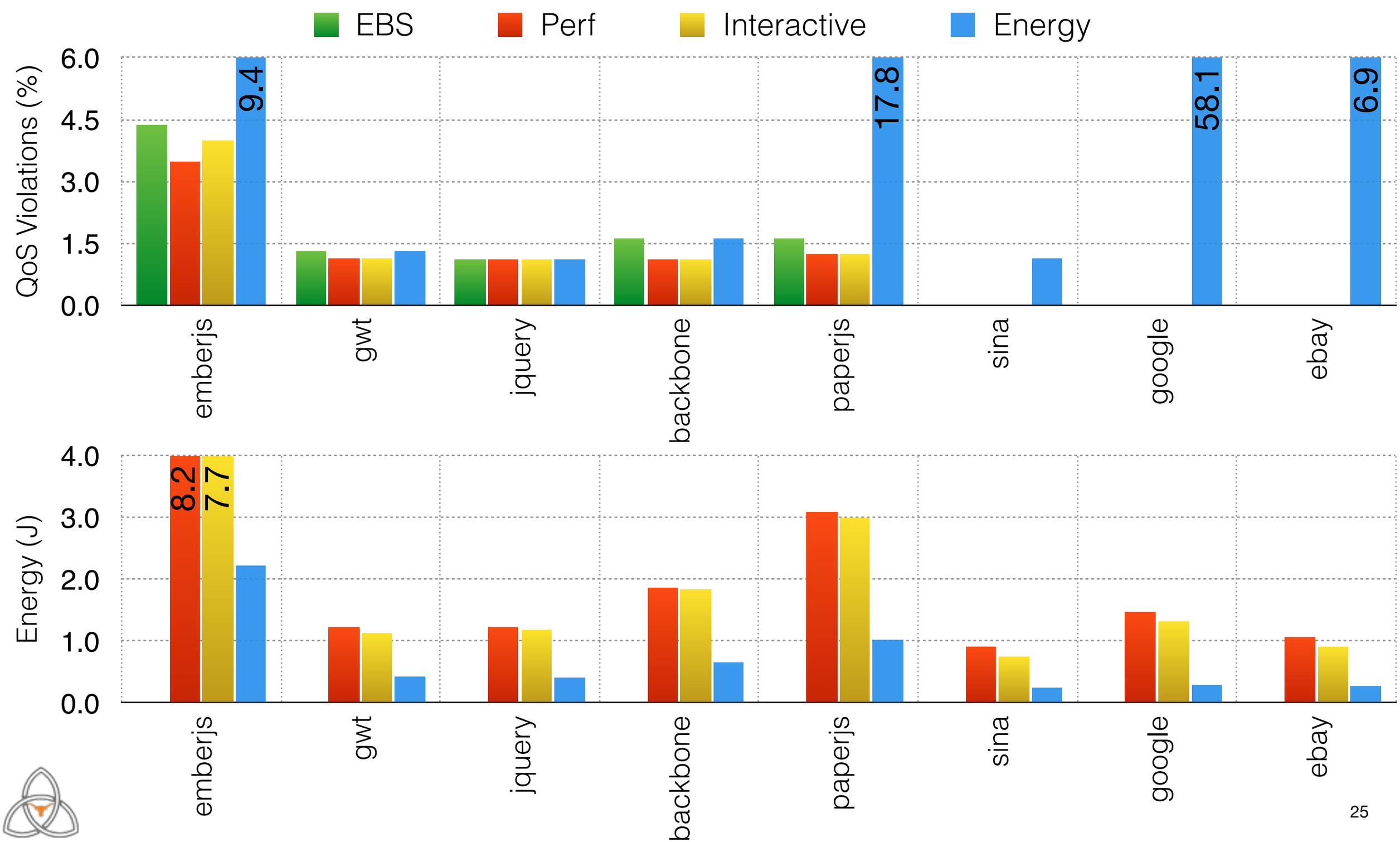

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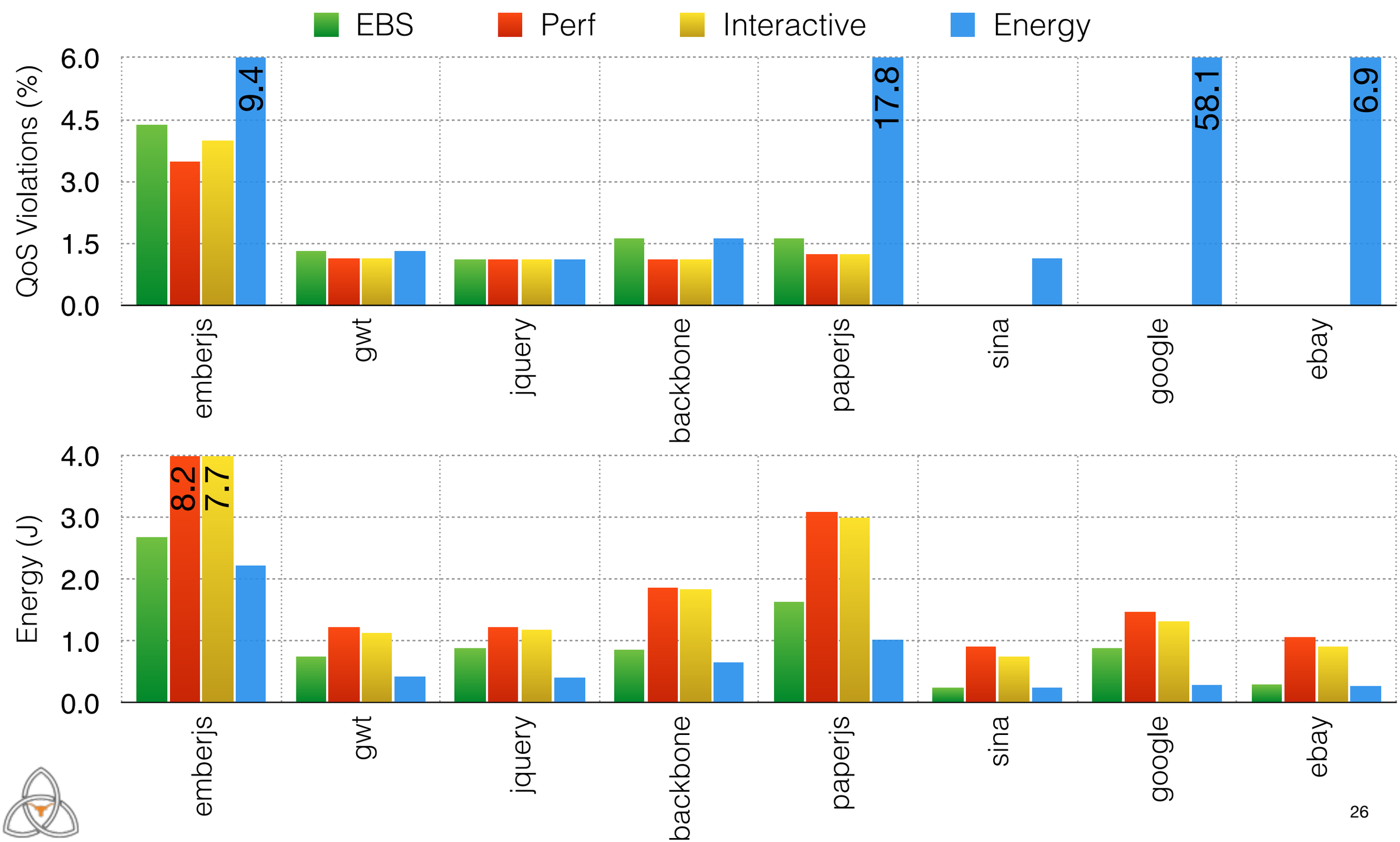

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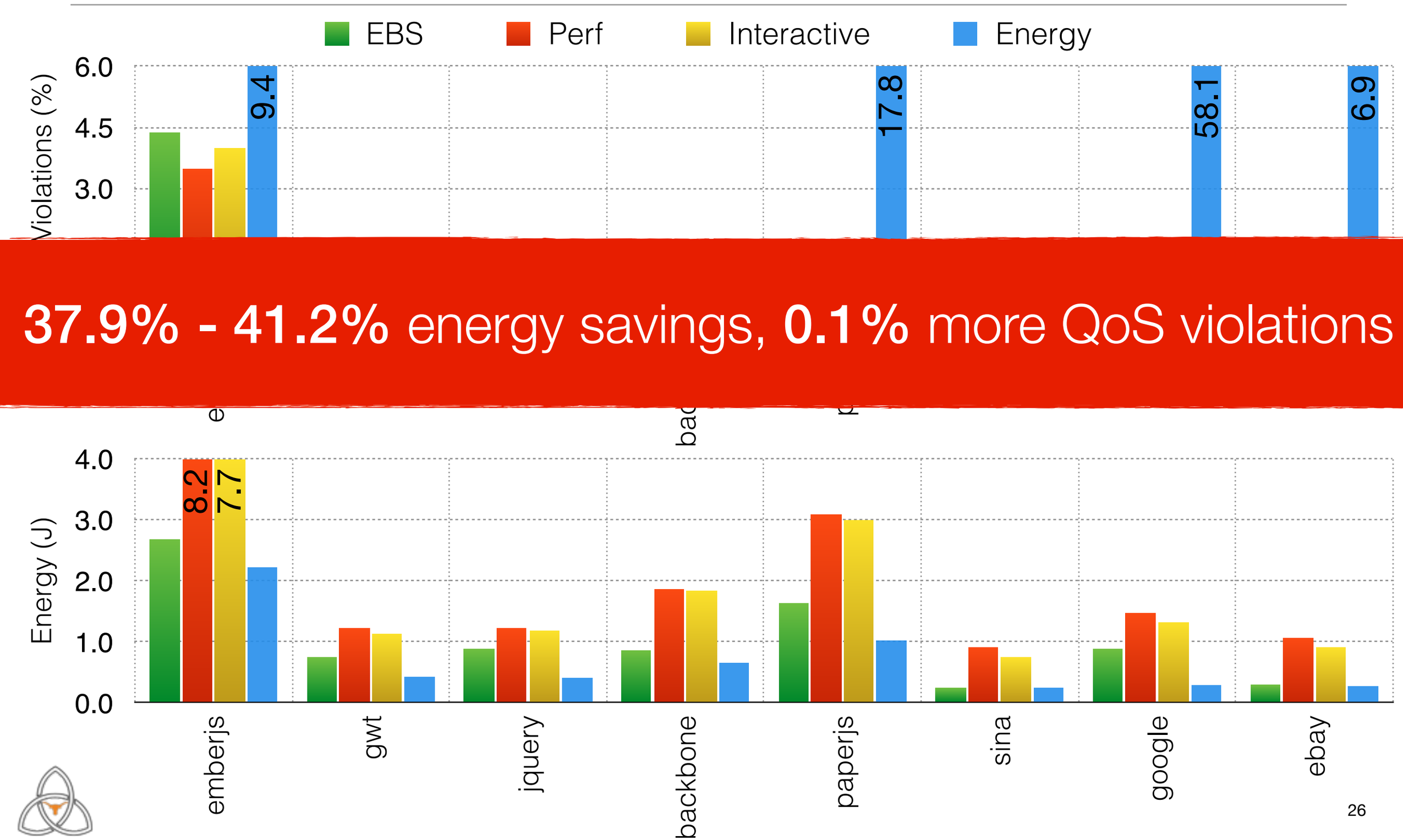
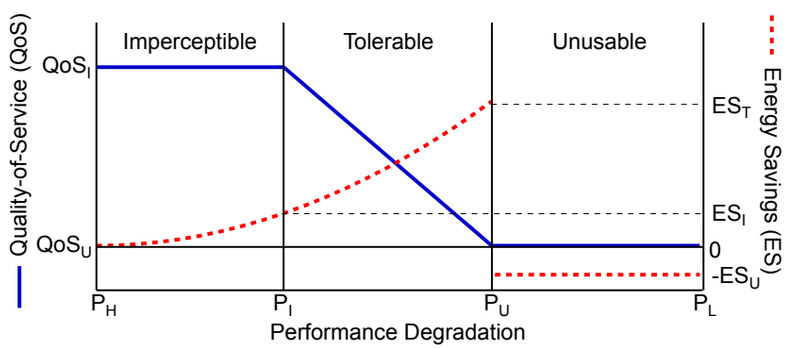


37.9% - 41.2% energy savings, **0.1%** more QoS violations

What Have We Learnt So Far

- User **interactivity** and **human perceptibility** are important because it has economic ramifications and impacts user device choice, as well as end-user satisfaction

What Have We Learnt So Far



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- Need a systematic way of understanding and QoS-energy trade-offs. To that end we advocate **eQoS** to strike a balance between user satisfaction and energy reduction

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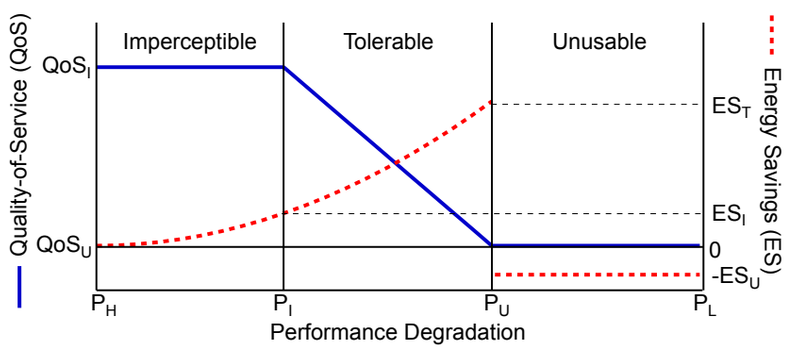
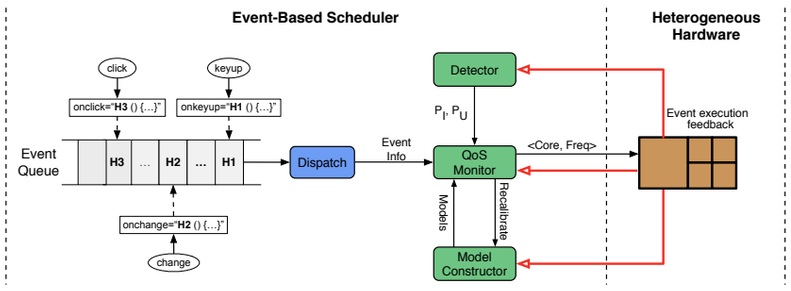


- Need a systematic way of understanding and QoS-energy trade-offs. To that end we advocate **eQoS** to strike a balance between user satisfaction and energy reduction



- Develop the event-based scheduling (**EBS**) mechanism that exploits the fundamental event-driven execution pattern of mobile applications to achieve better eQoS

Mobile is One Example

Web

Mobile

Mobile is One Example

Web

Mobile

Sensor networks

Cloud

Internet-of-Things

Mobile is One Example

Web

Mobile

Sensor networks

Cloud

Internet-of-Things

Event-based processing is a fundamental computation pattern.

Mobile is One Example

Web | Mobile | Sensor networks | Cloud | Internet-of-Things

Event-based processing is a fundamental computation pattern.

- Another talk @ **Best of CAL session**
- Wednesday after the keynote
- How computer architects can improve Web technologies

Thank you