Skua: Extending Distributed Tracing Vertically into the Linux Kernel

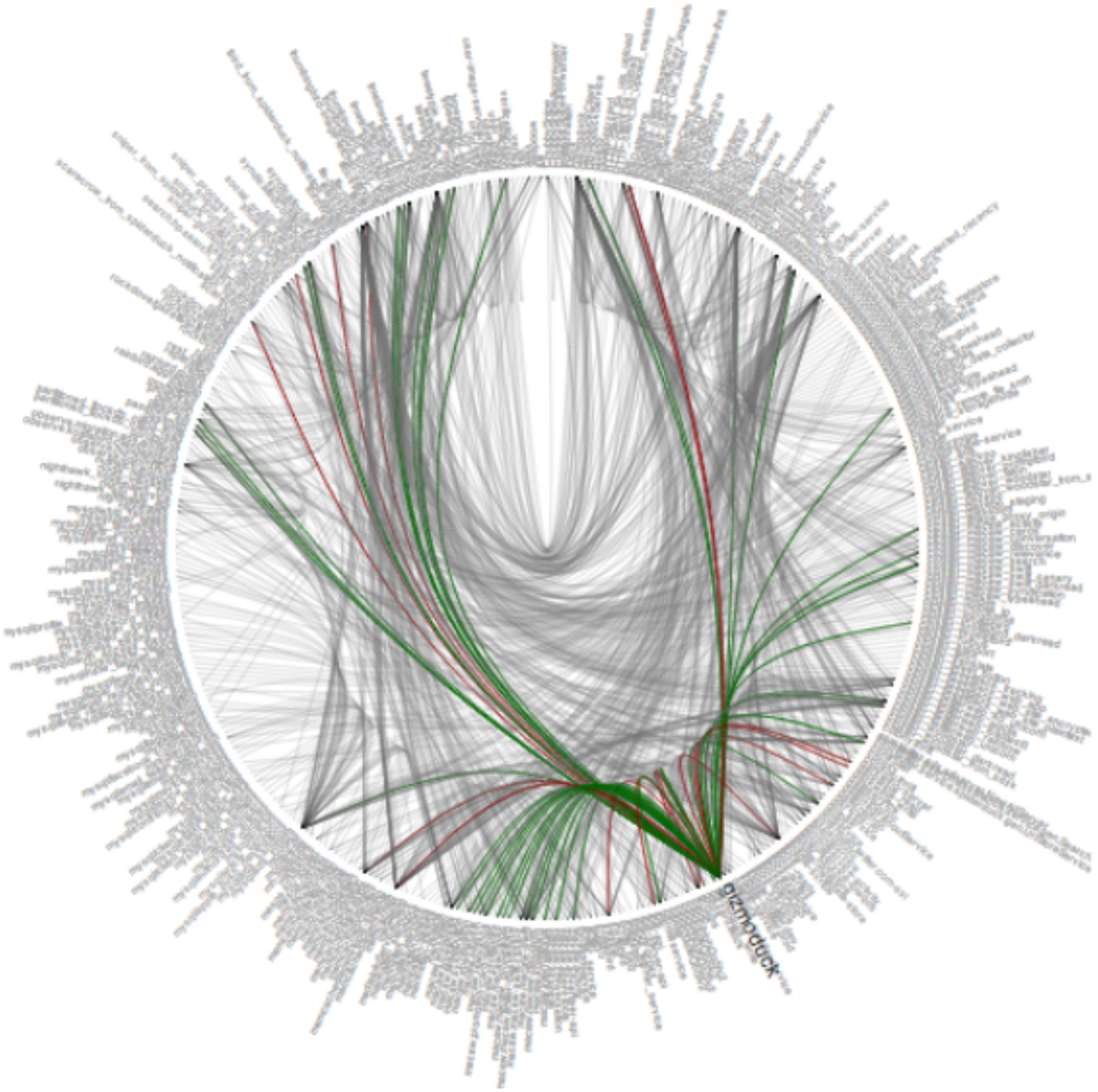
Harshal Sheth and Andrew Sun

Distributed Systems

- Complex applications are no longer monolithic
    - Modular/agile development
    - Continuous deployment
    - Independent scaling

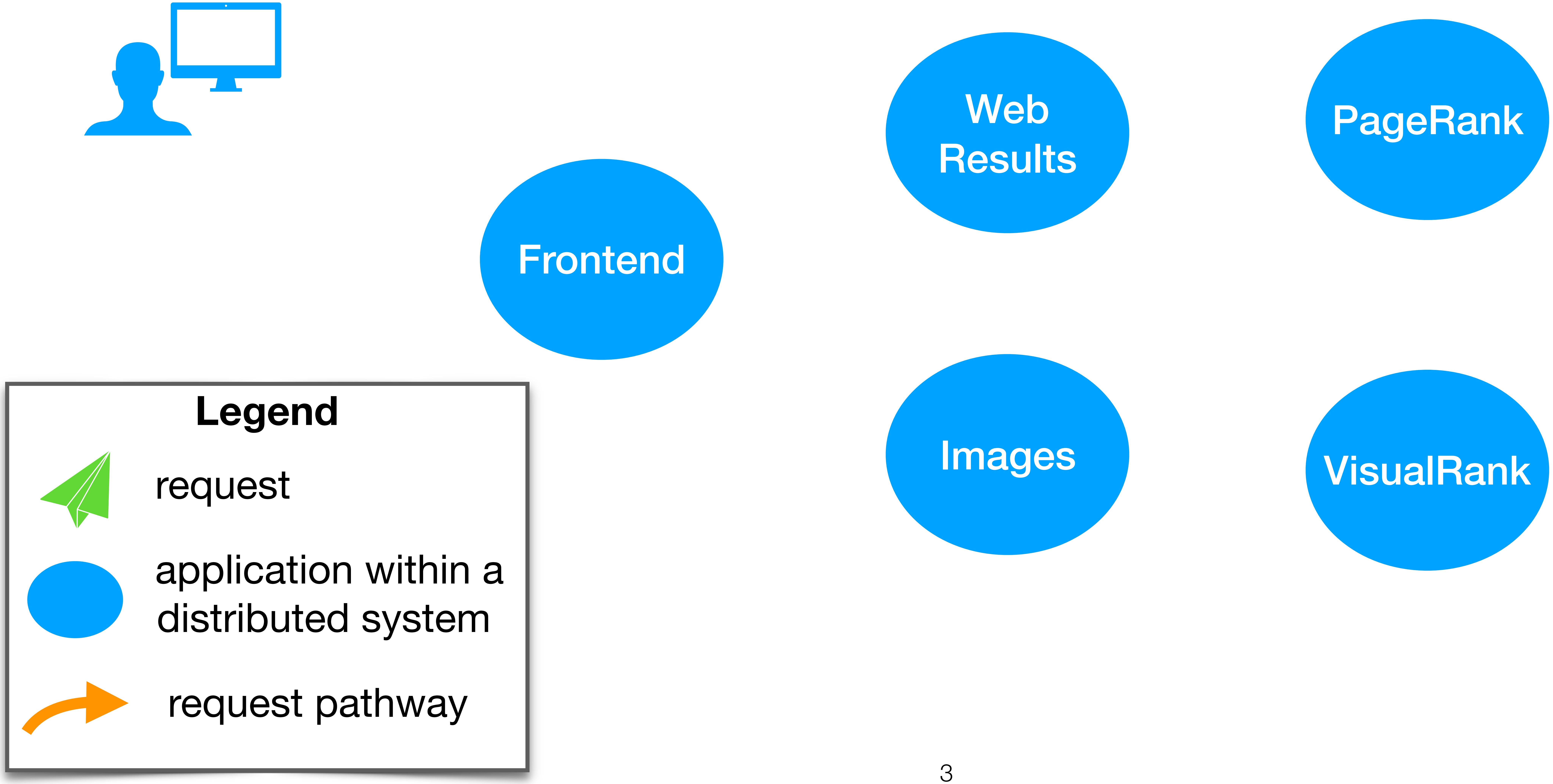
Distributed Systems

- Complex applications are no longer monolithic
  - Modular/agile development
  - Continuous deployment
  - Independent scaling
- Increasingly seen in large companies
- Hard to debug



Twitter, 2013

Example Distributed System



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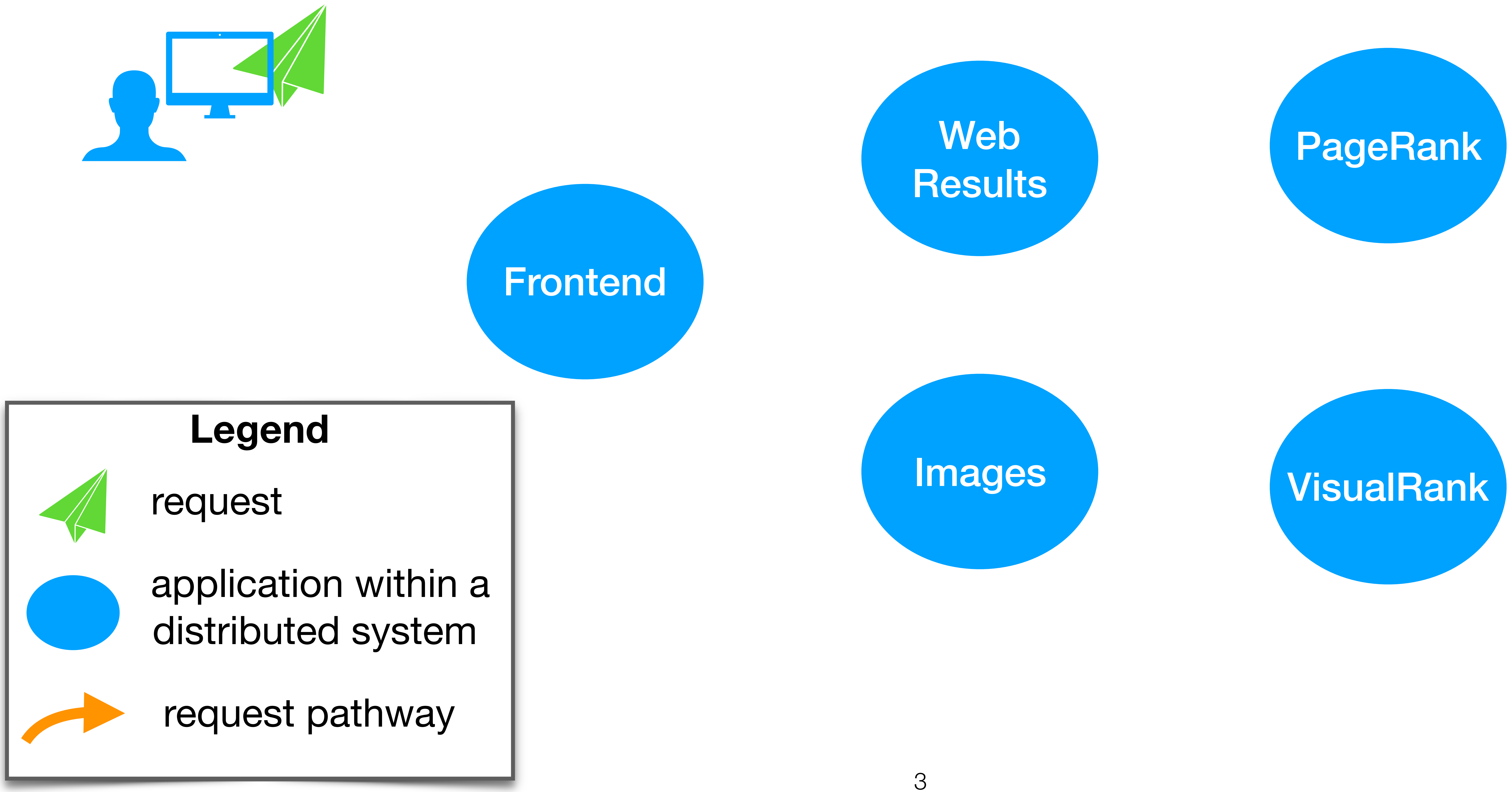

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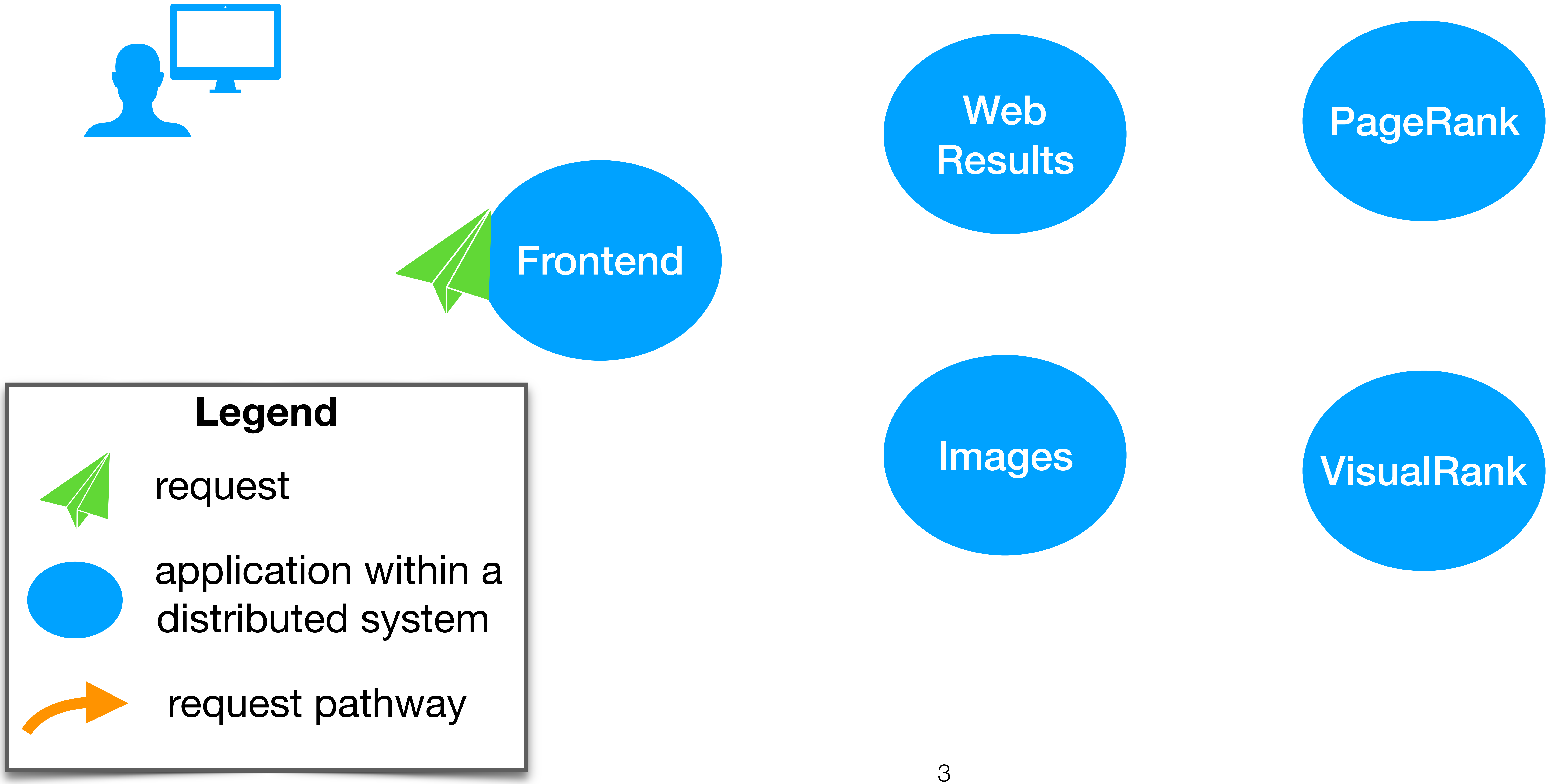

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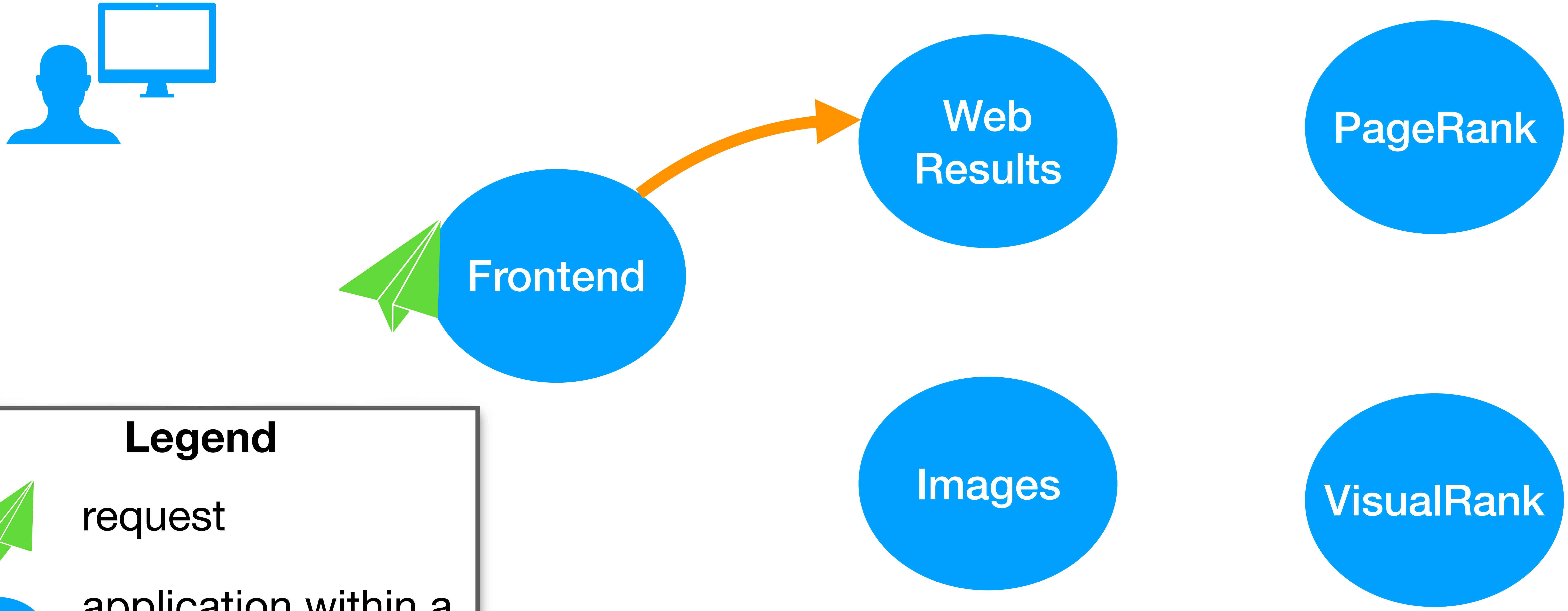


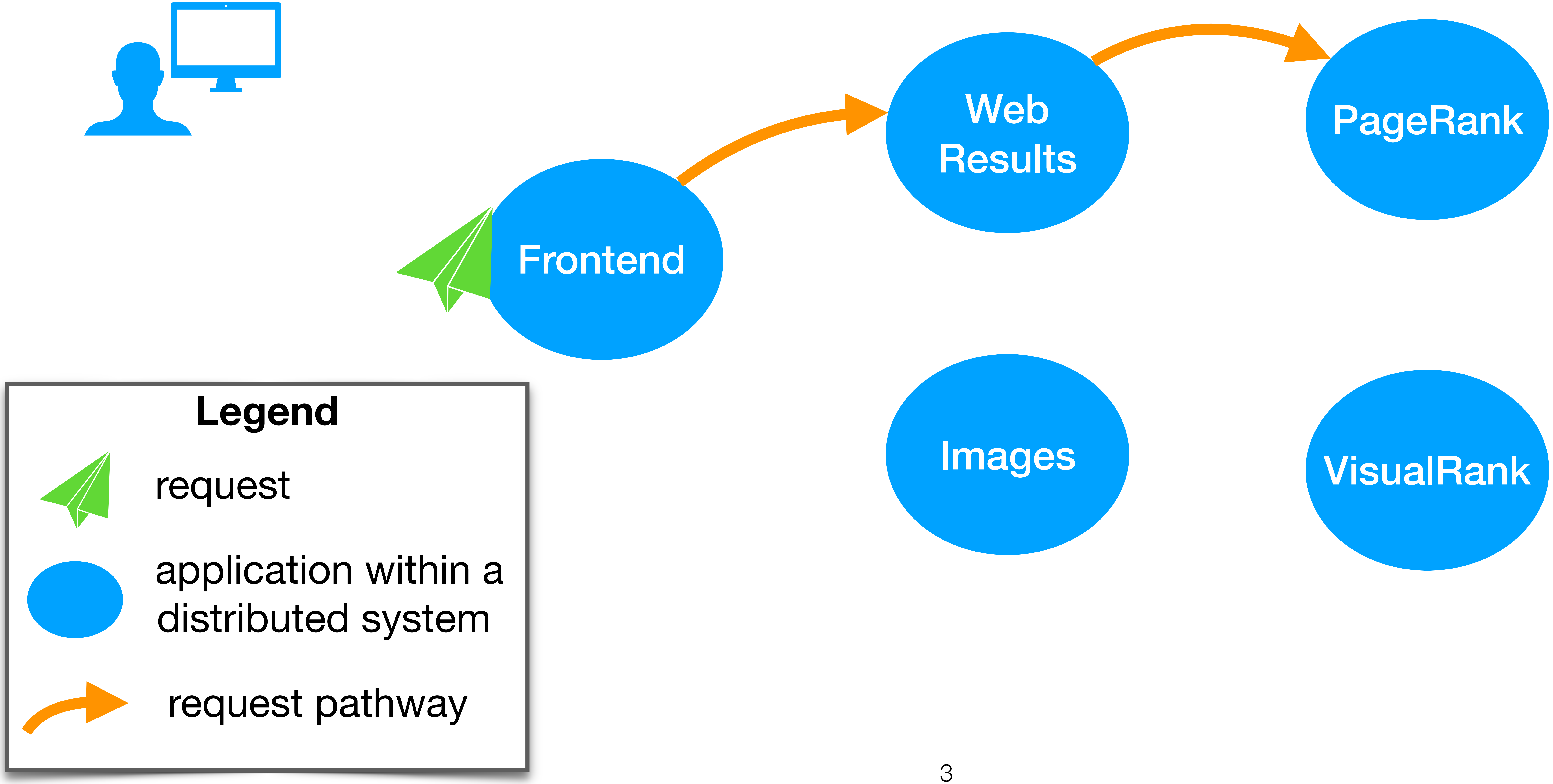
Legend

request

application within a distributed system

request pathway

Example Distributed System



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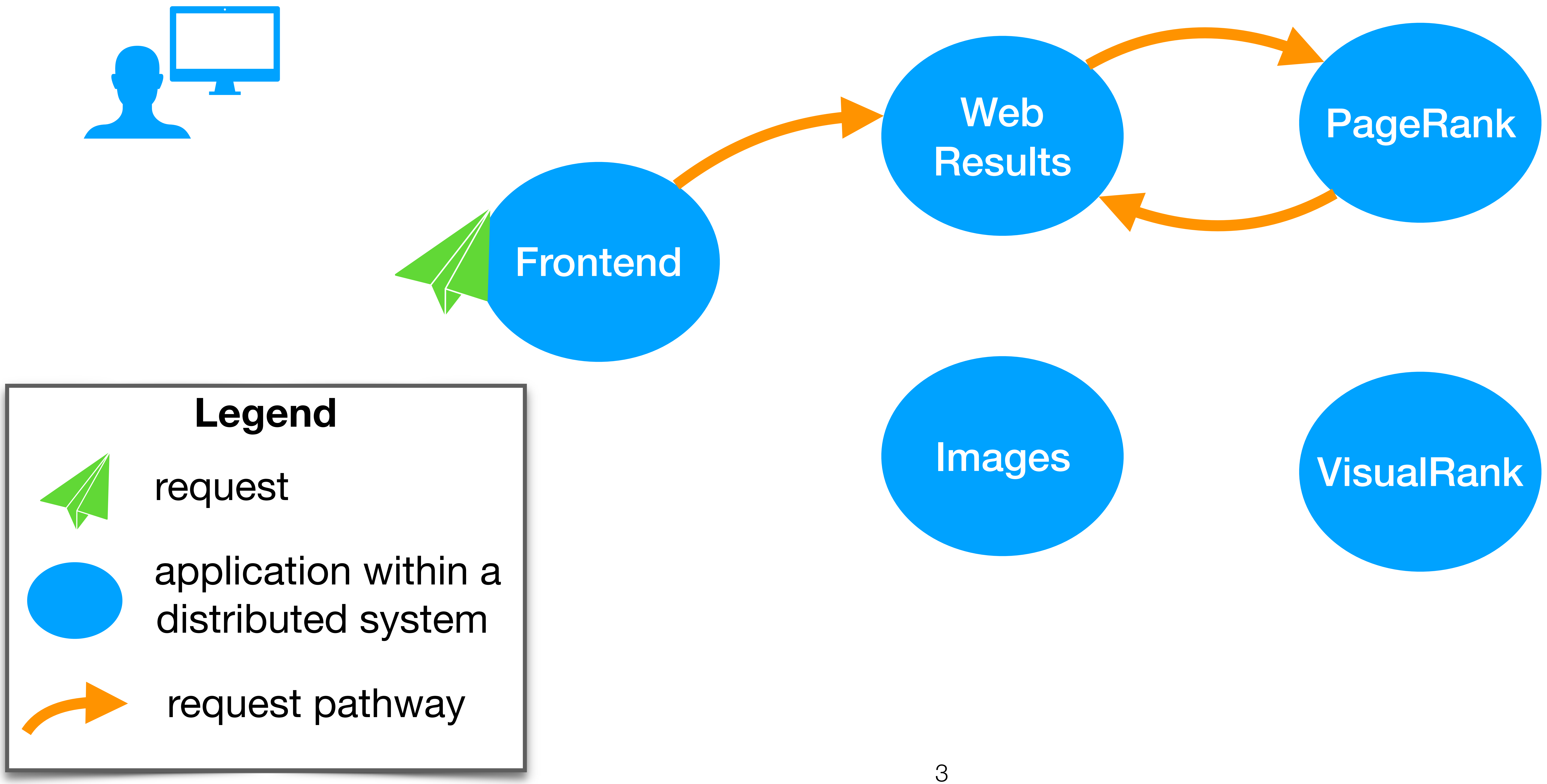

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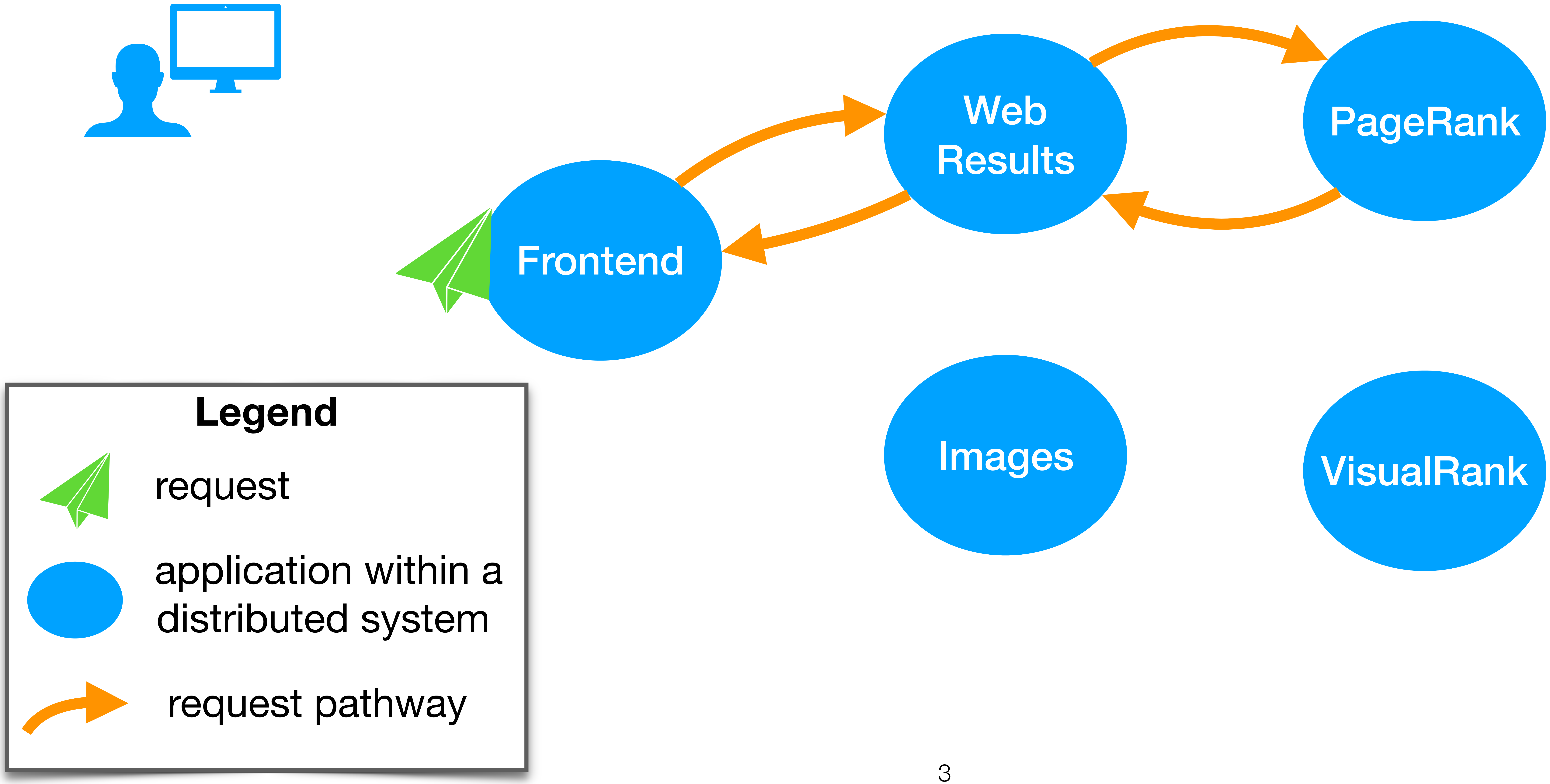

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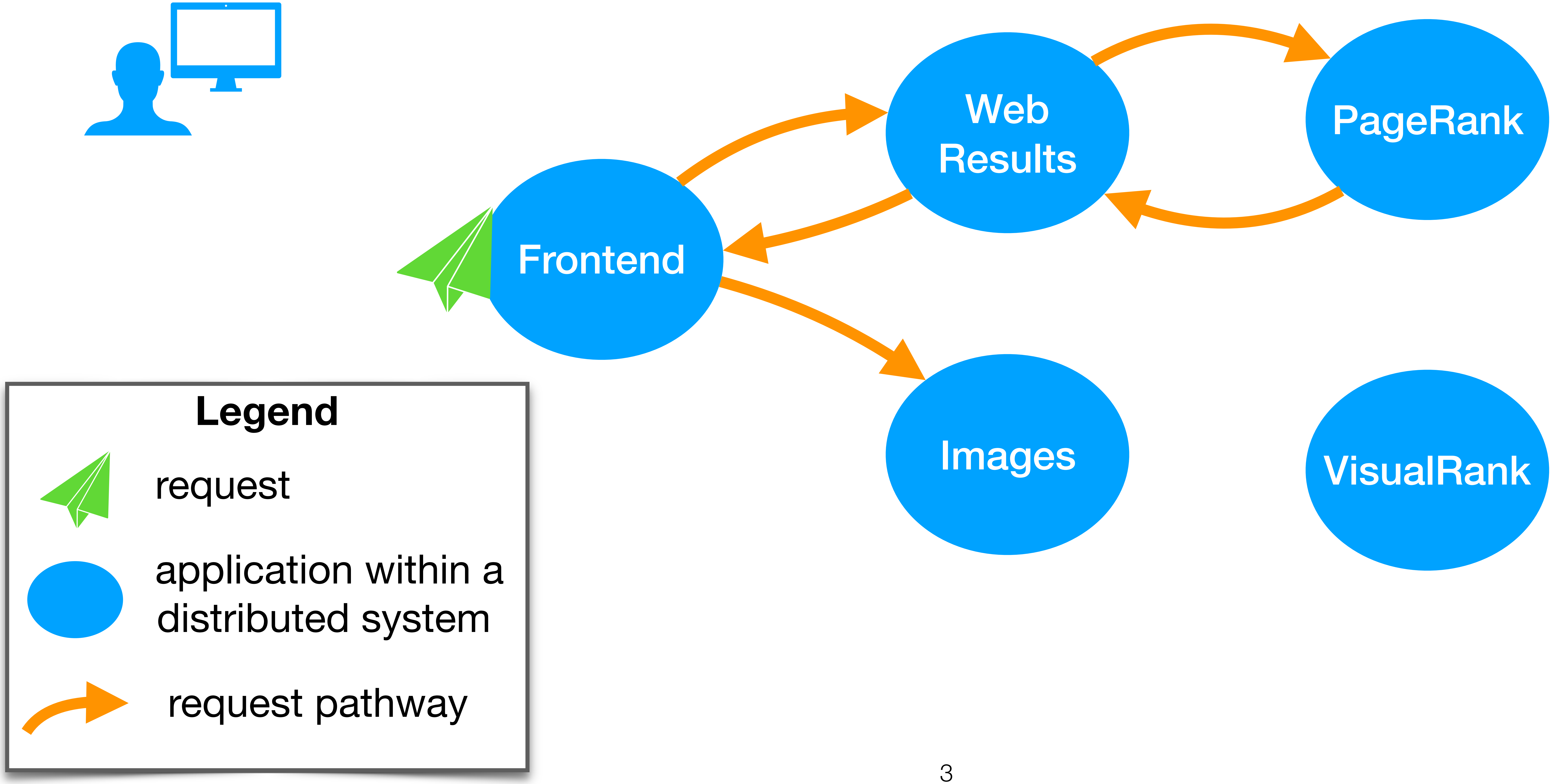

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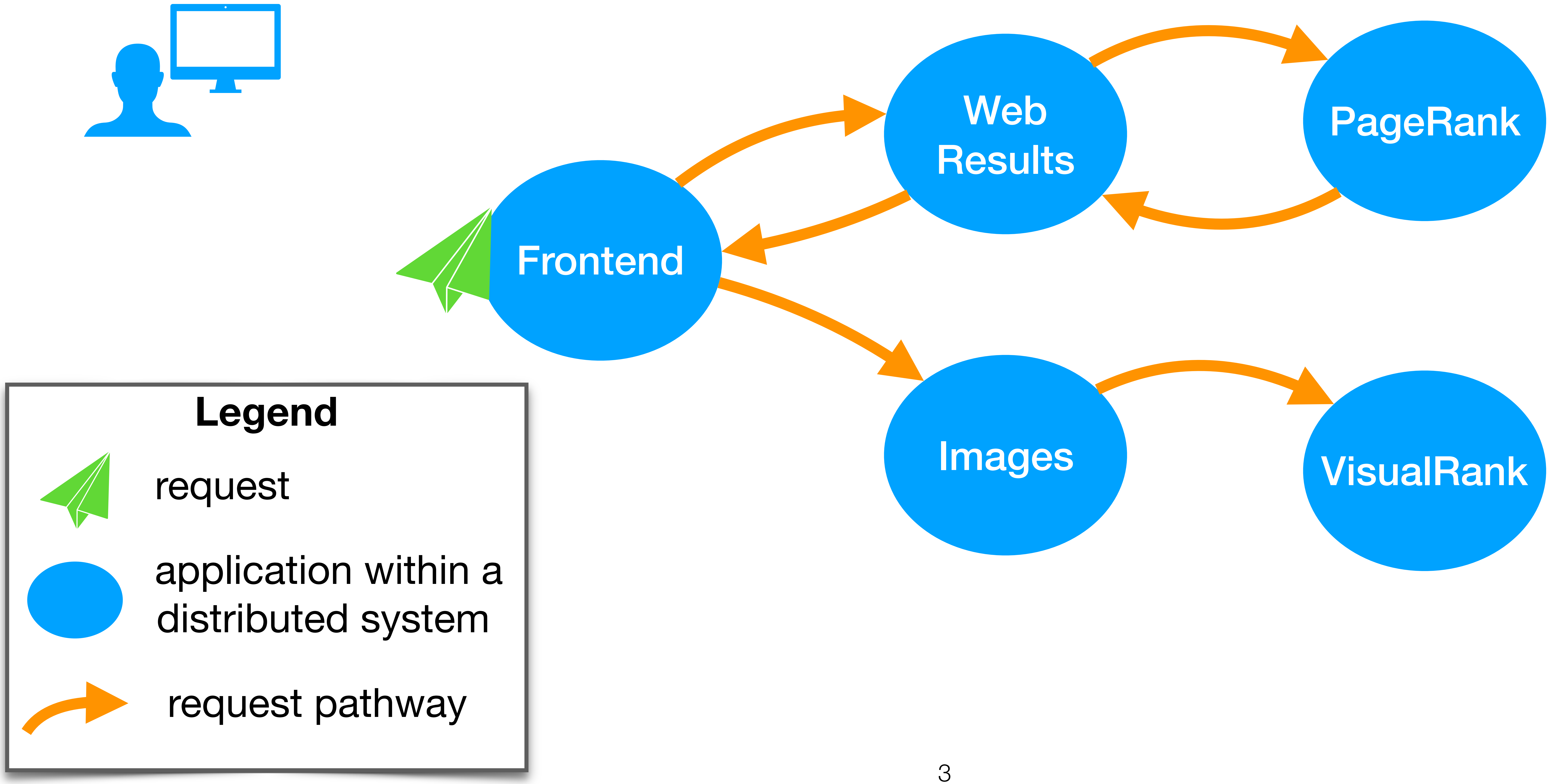

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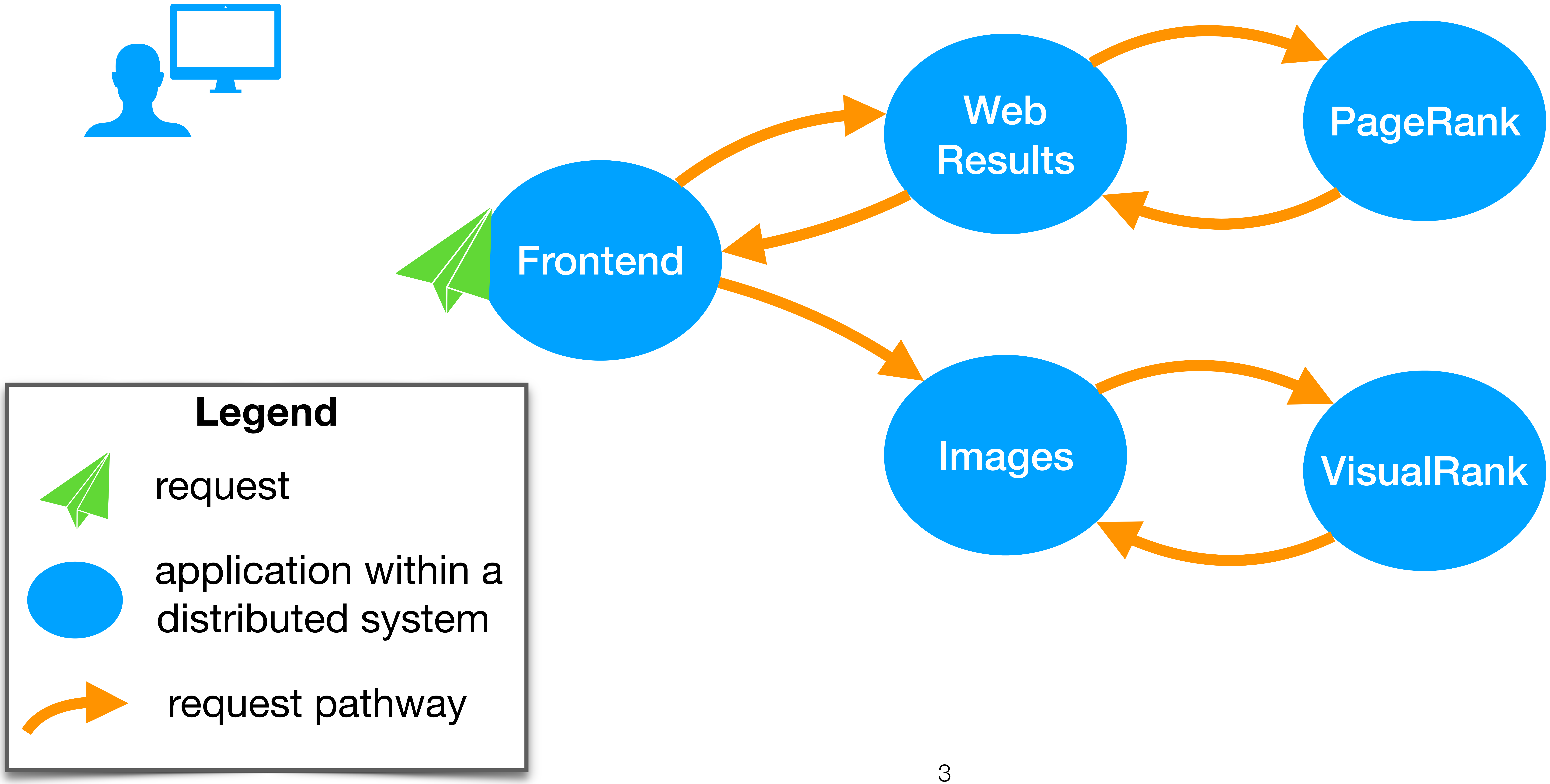

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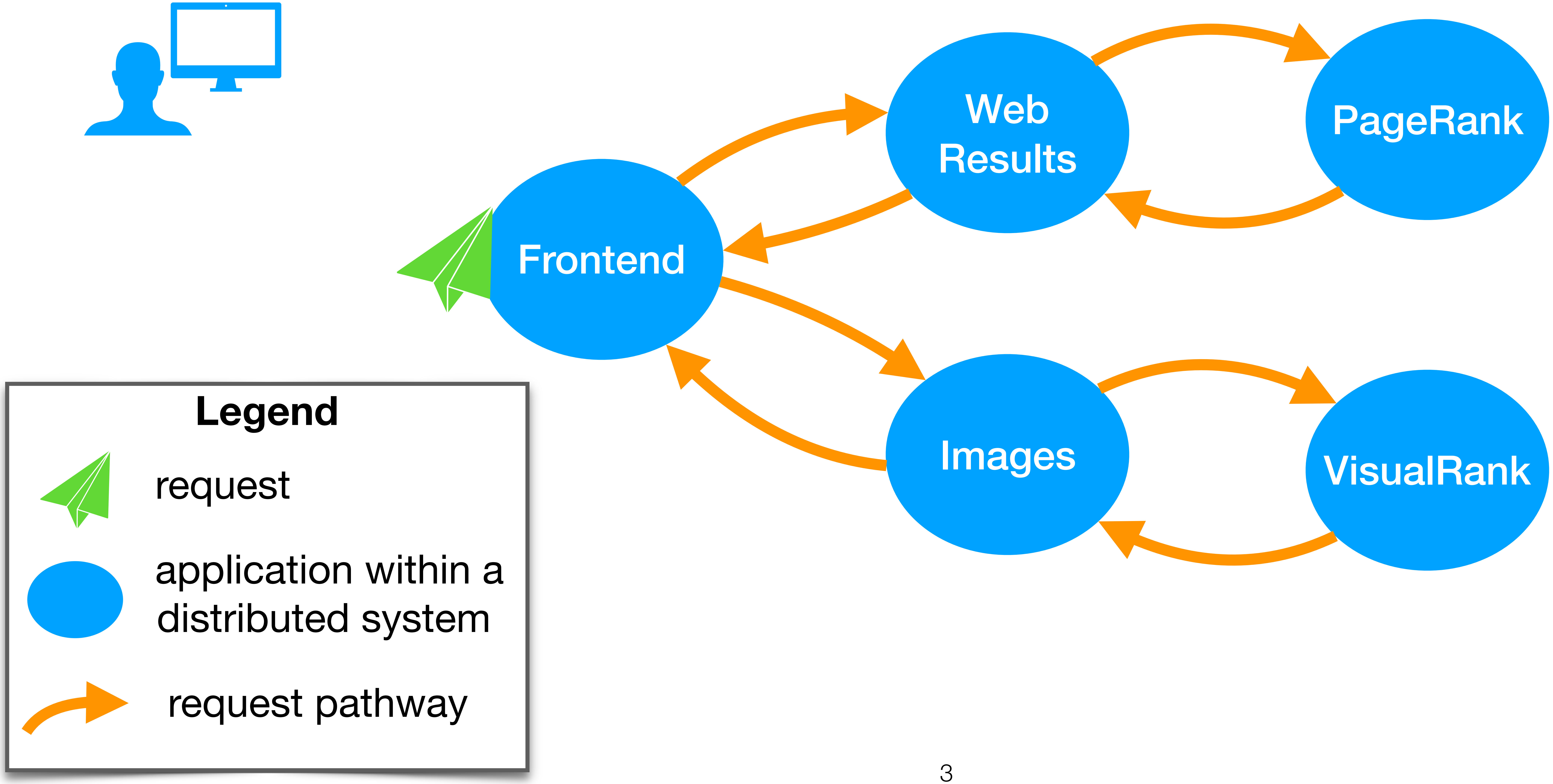

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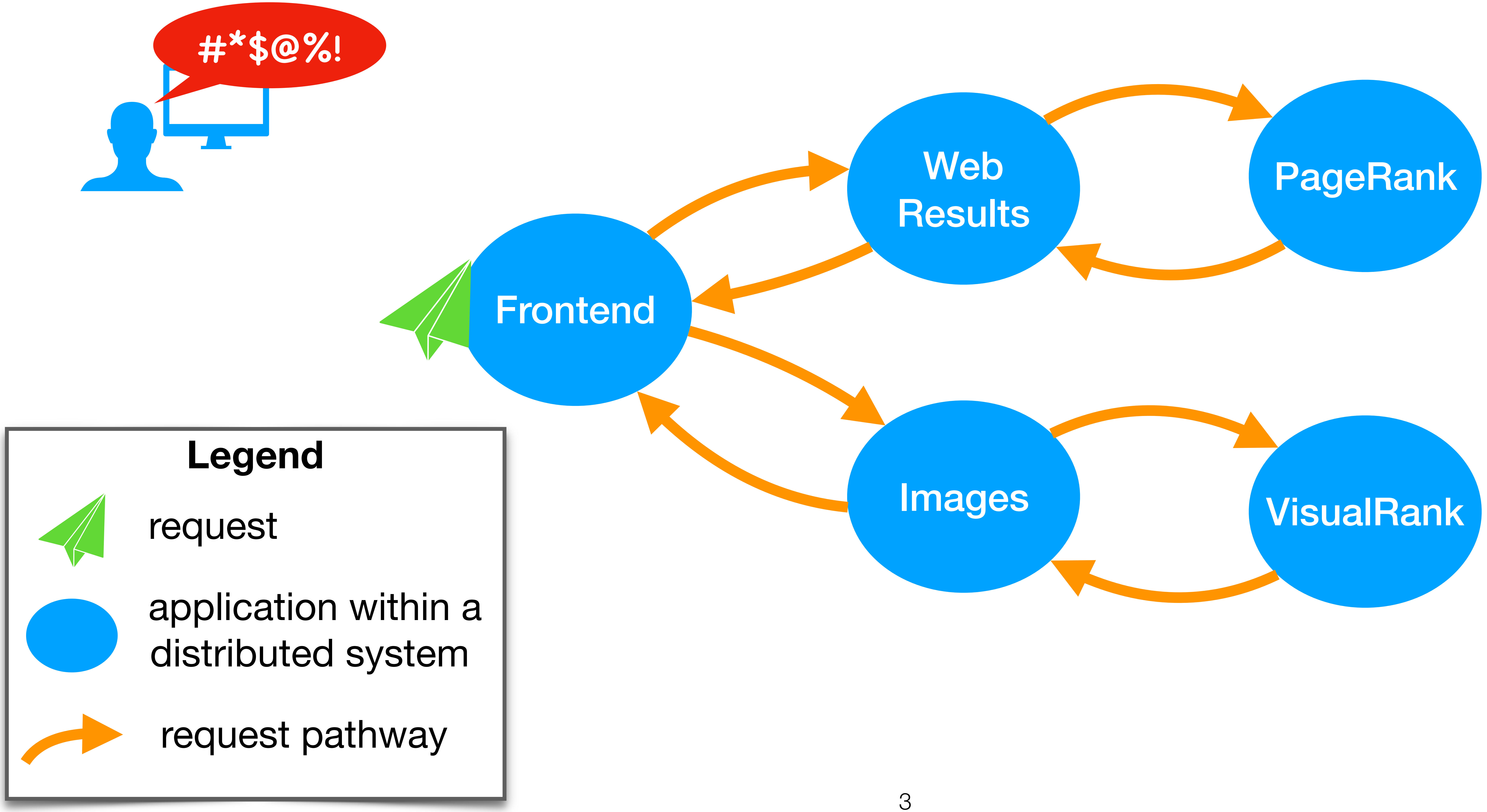

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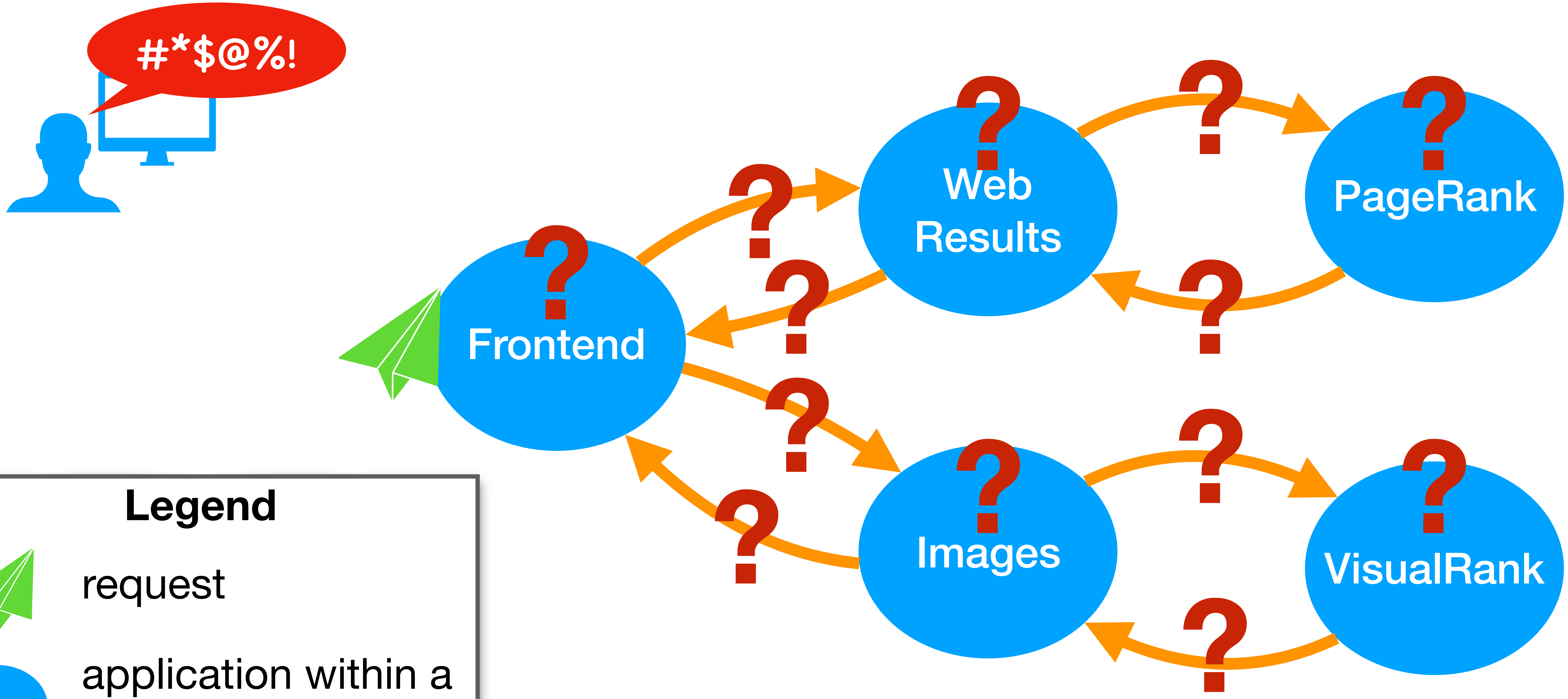

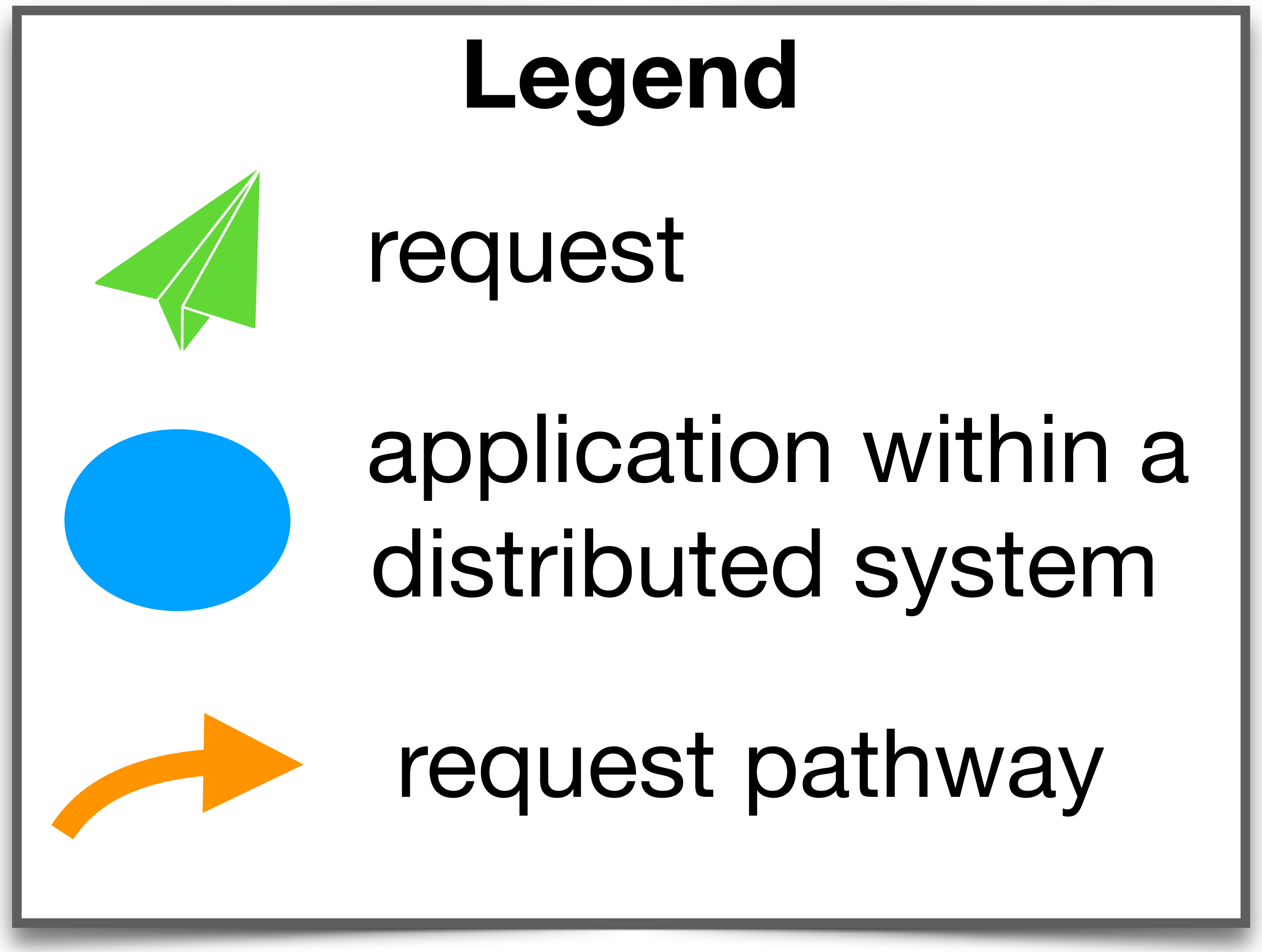

Distributed Tracing

- Monitoring and troubleshooting distributed systems

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  - Discovering latency issues

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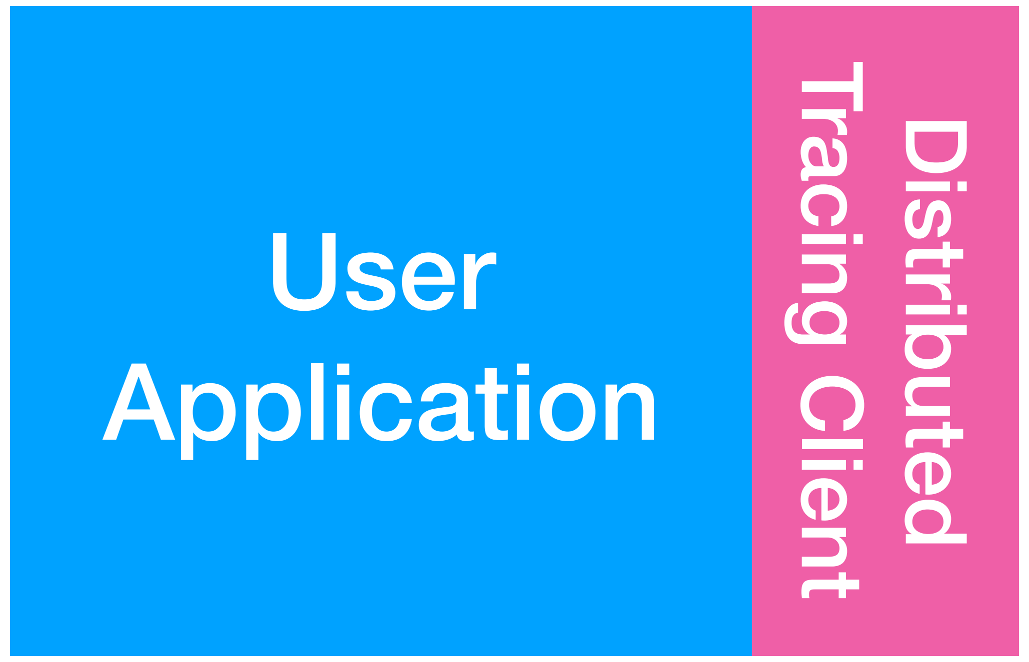
Distributed Tracing

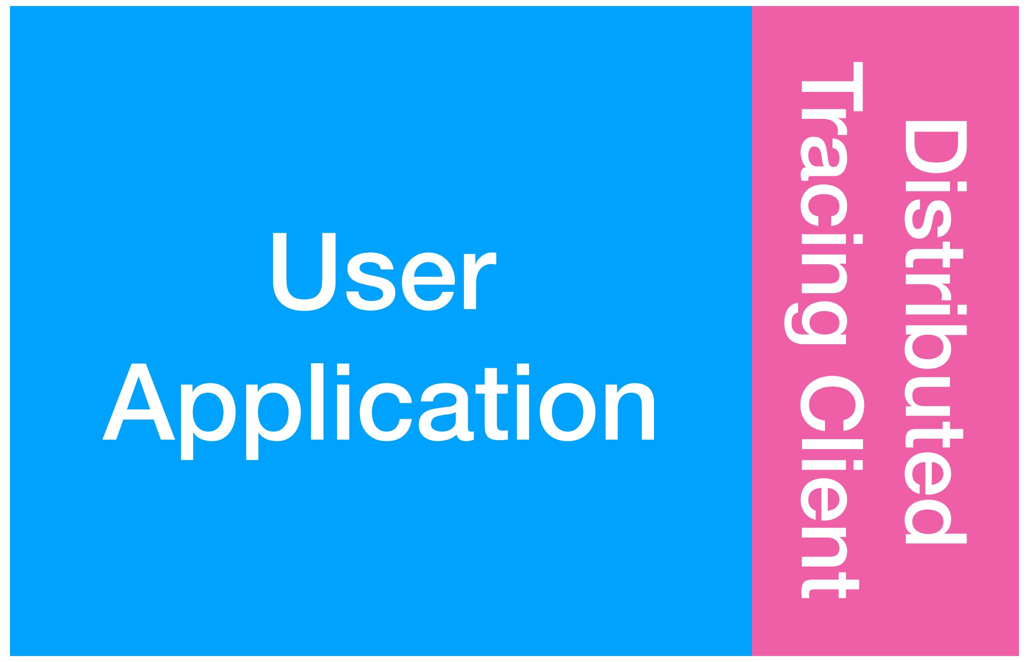
- Monitoring and troubleshooting distributed systems
  - Discovering latency issues
  - Graphing service dependencies
  - Root-cause analysis of backend issues
  - Tracing a specific request through the entire system

What does distributed tracing miss?



What does distributed tracing miss?

- There's more to performance than meets the eye of existing distributed tracing tools



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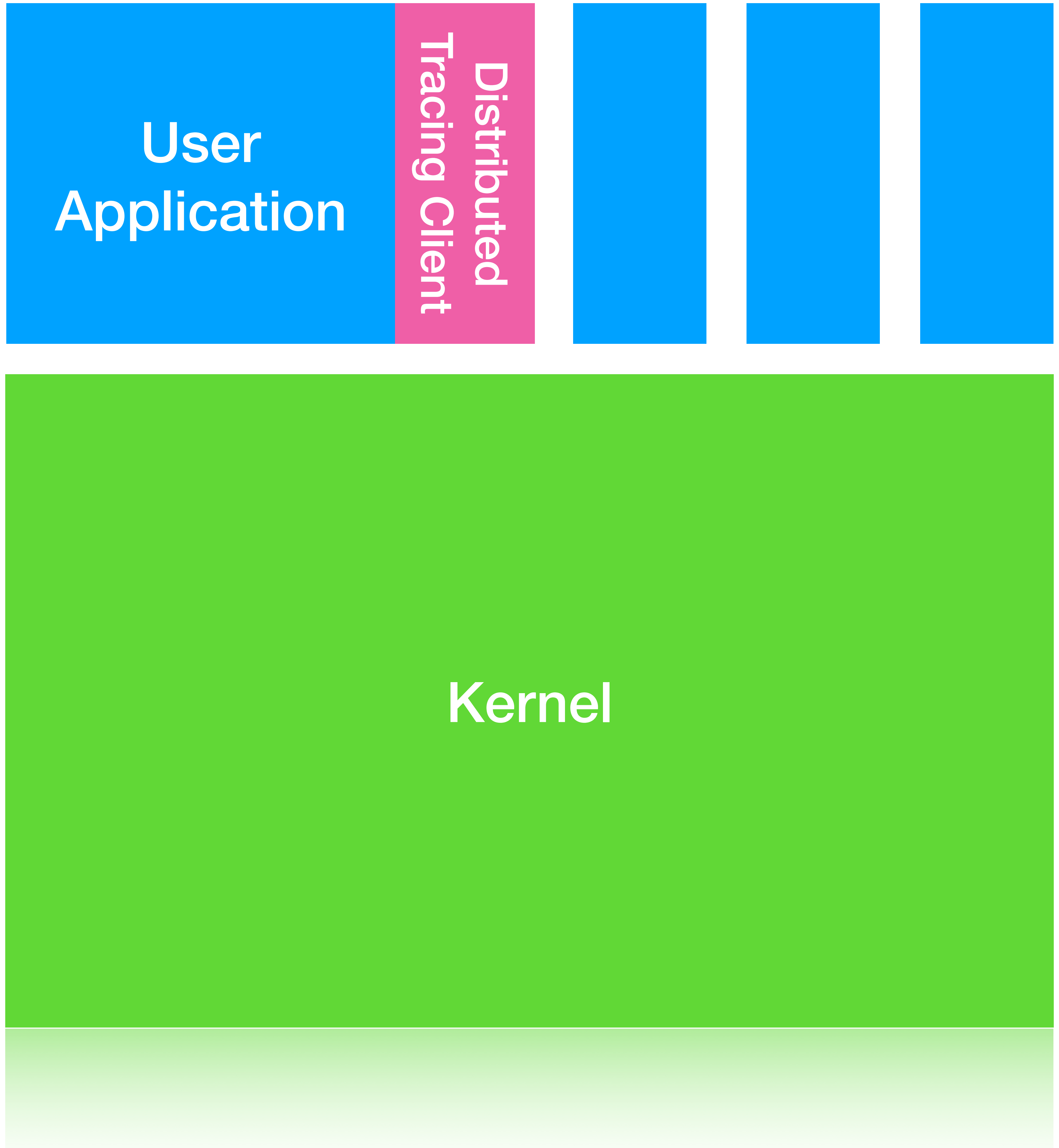
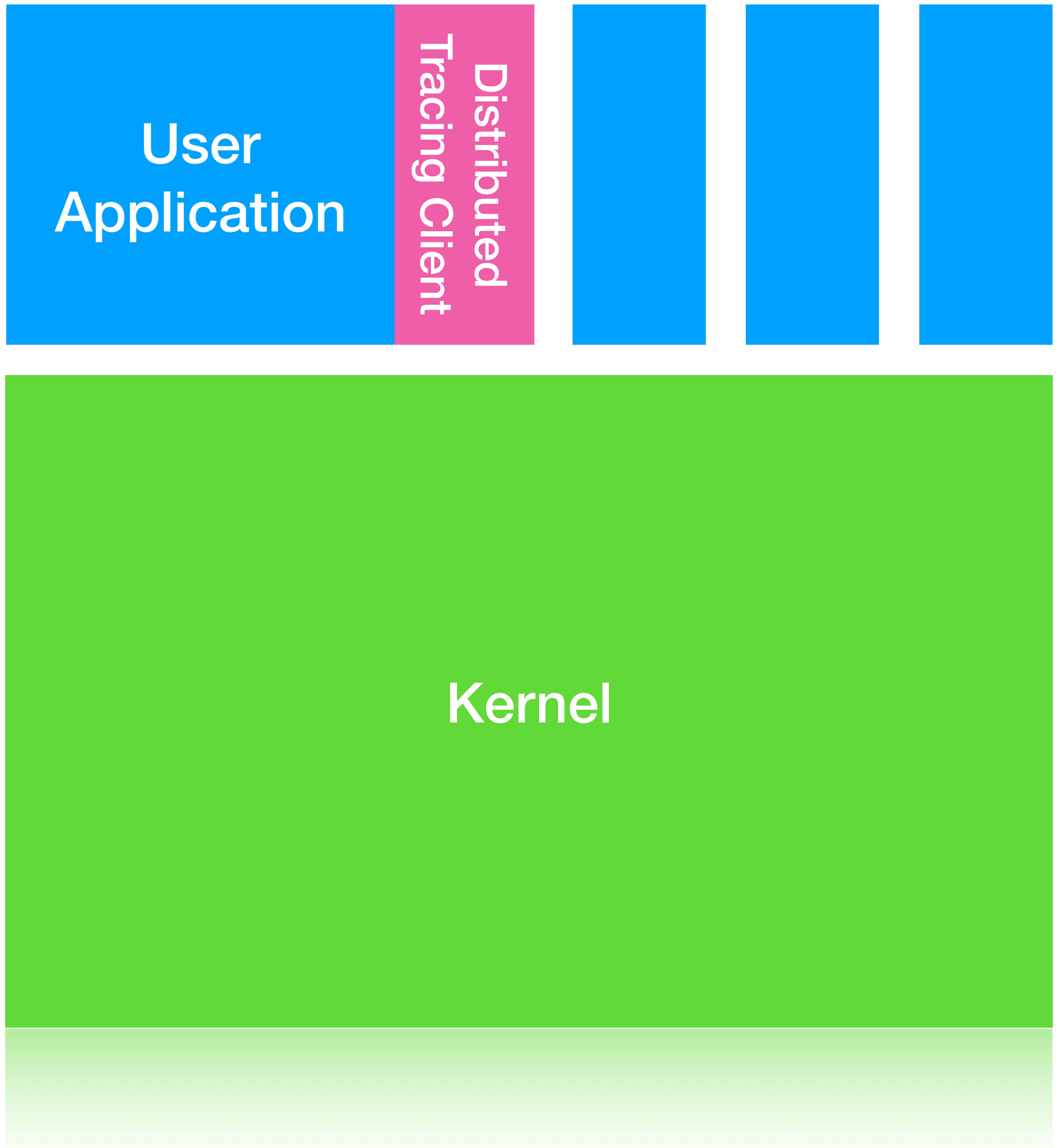
  - Kernel bugs
  - Security patches (e.g. Meltdown/Spectre)



What does distributed tracing miss?

- There's more to performance than meets the eye of existing distributed tracing tools
  - Contention between applications
  - Kernel bugs
  - Security patches (e.g. Meltdown/Spectre)
- Can we gain visibility regarding these issues via the kernel?



Our goal: extend distributed tracing into the kernel

Our Approach

Jaeger
distributed tracing
framework from Uber

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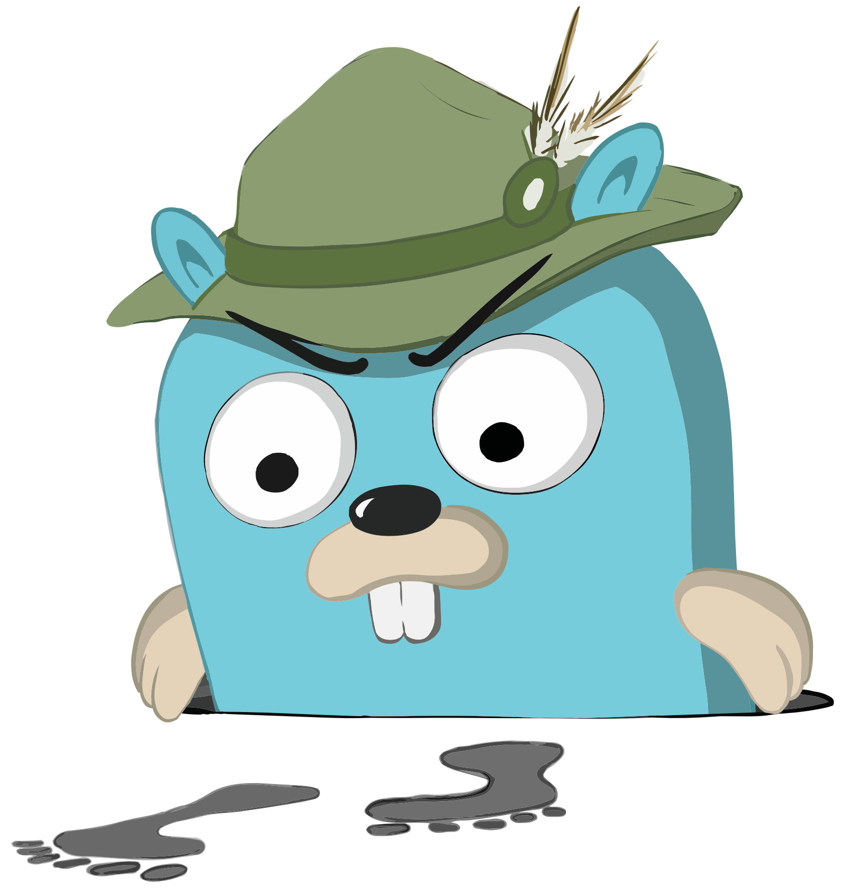

+

LTTng
Linux kernel
trace toolkit

Our Approach

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+

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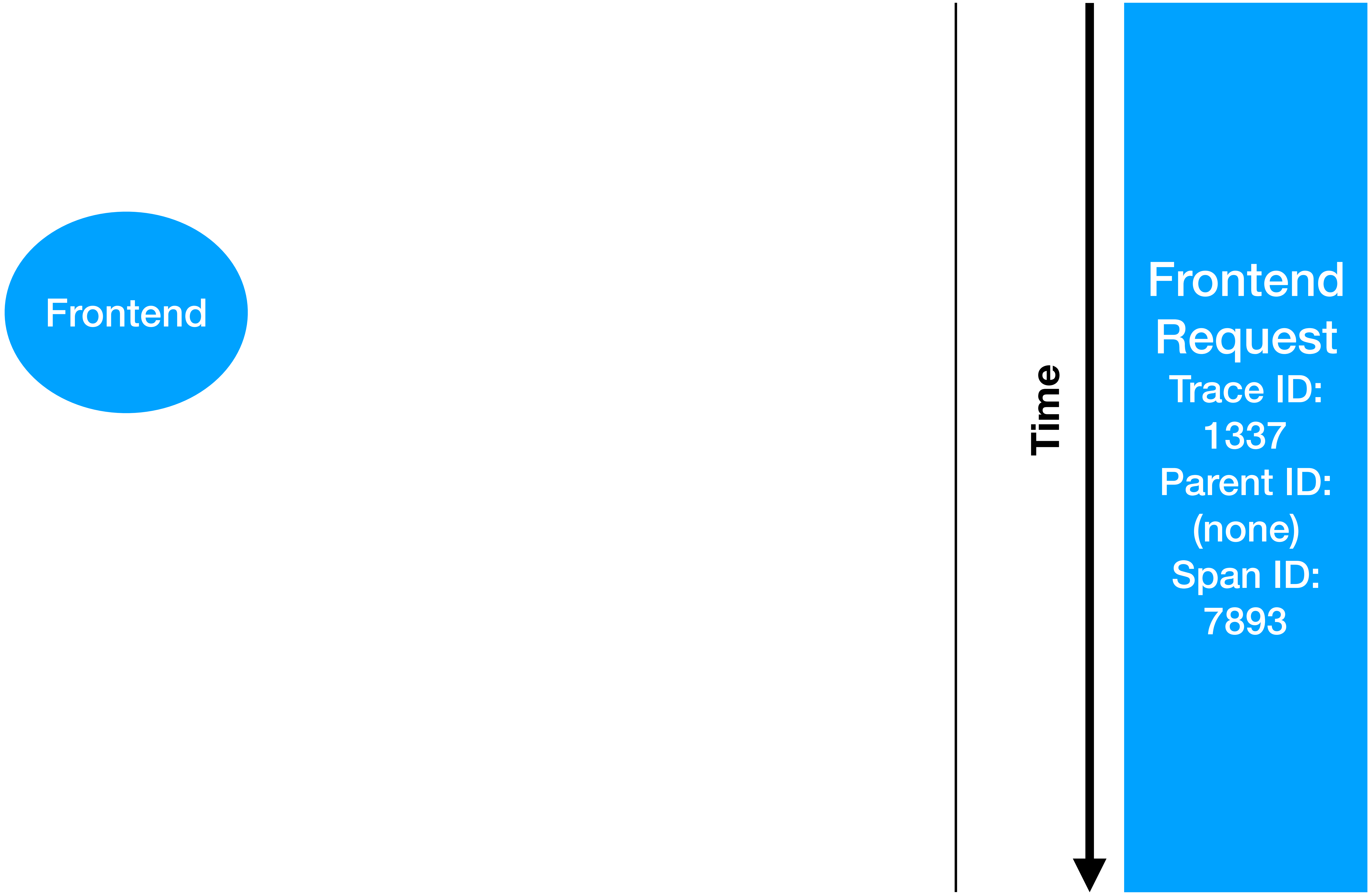
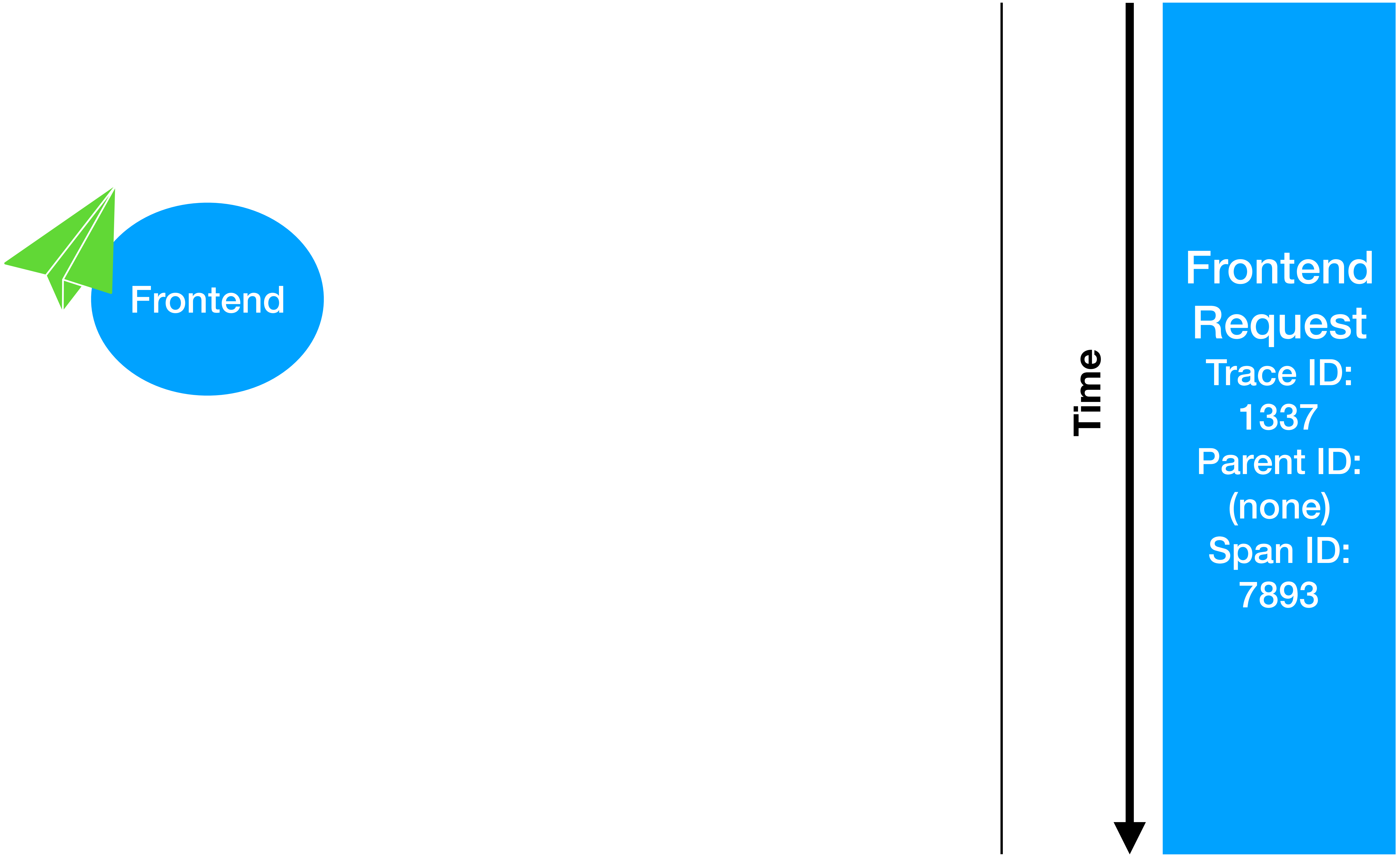
=

Skua

Traces and Spans



Traces and Spans



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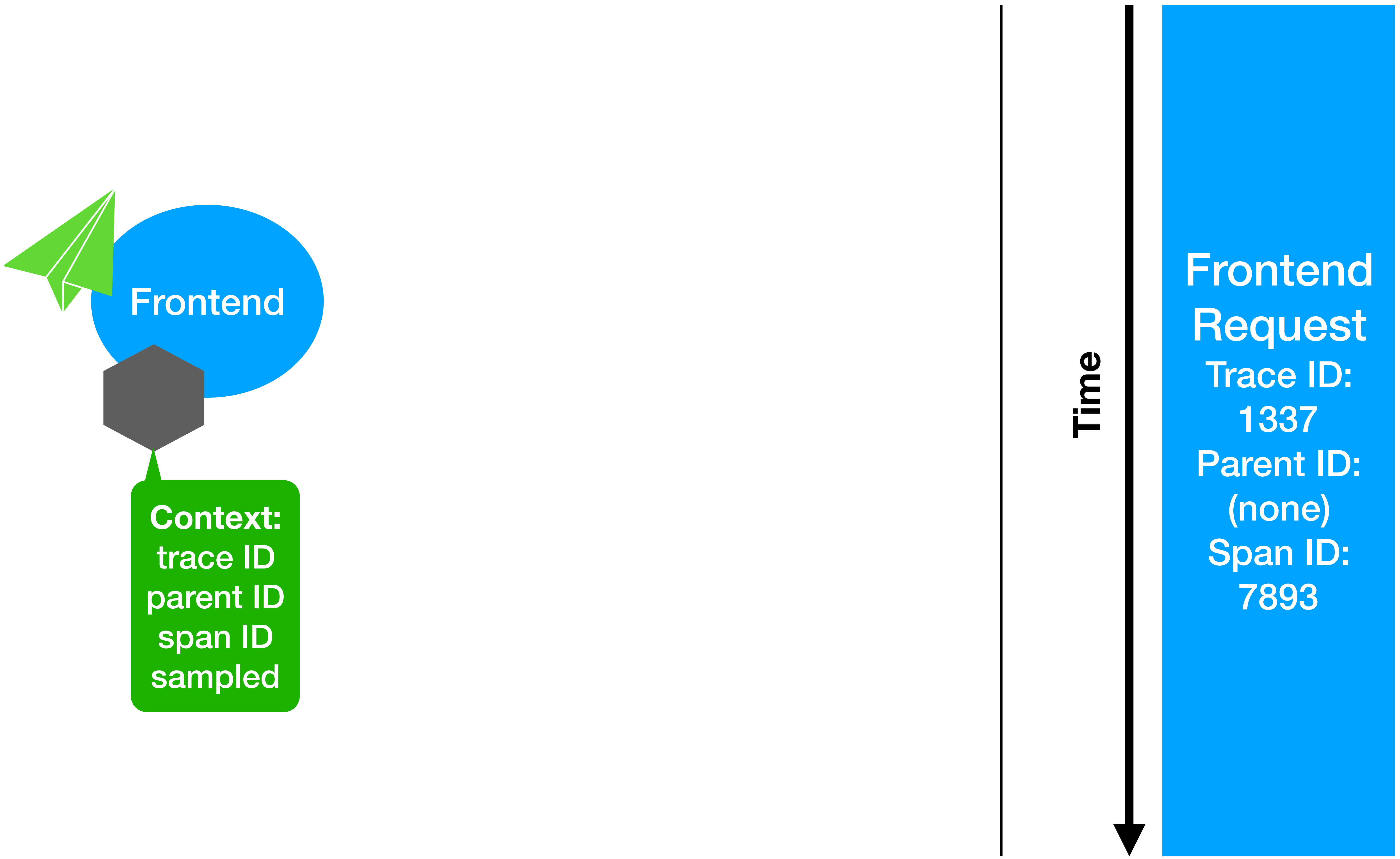

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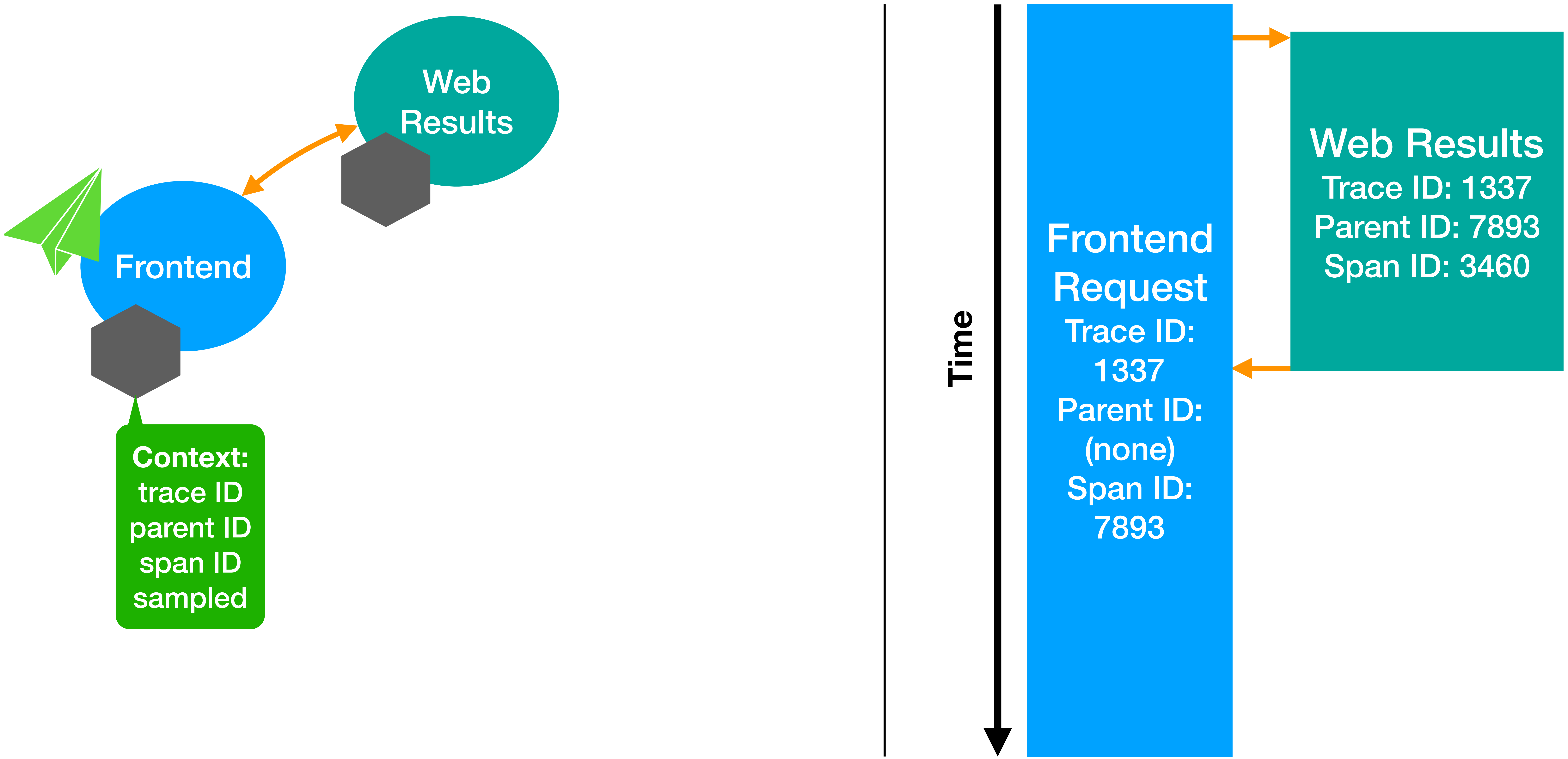

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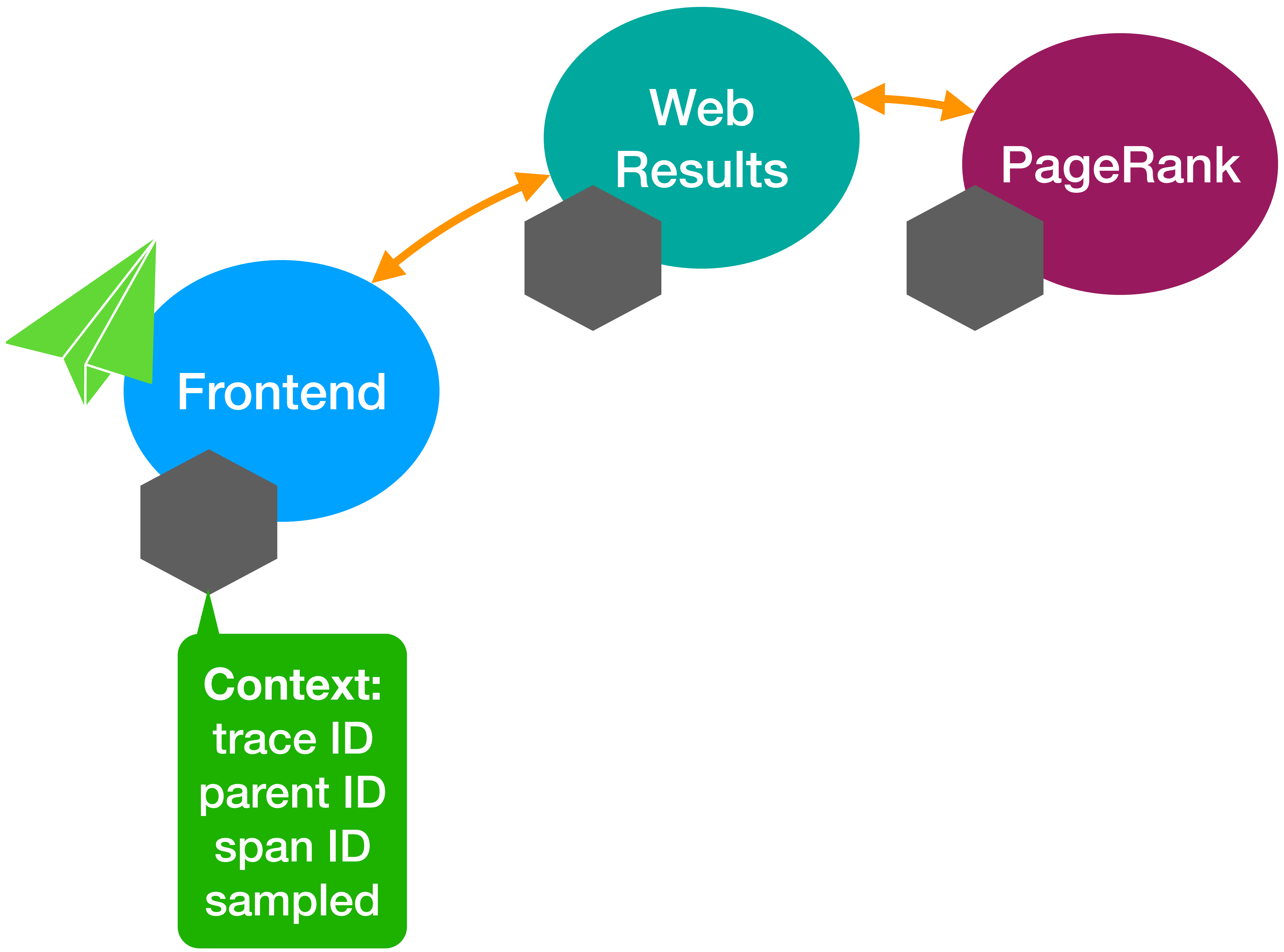

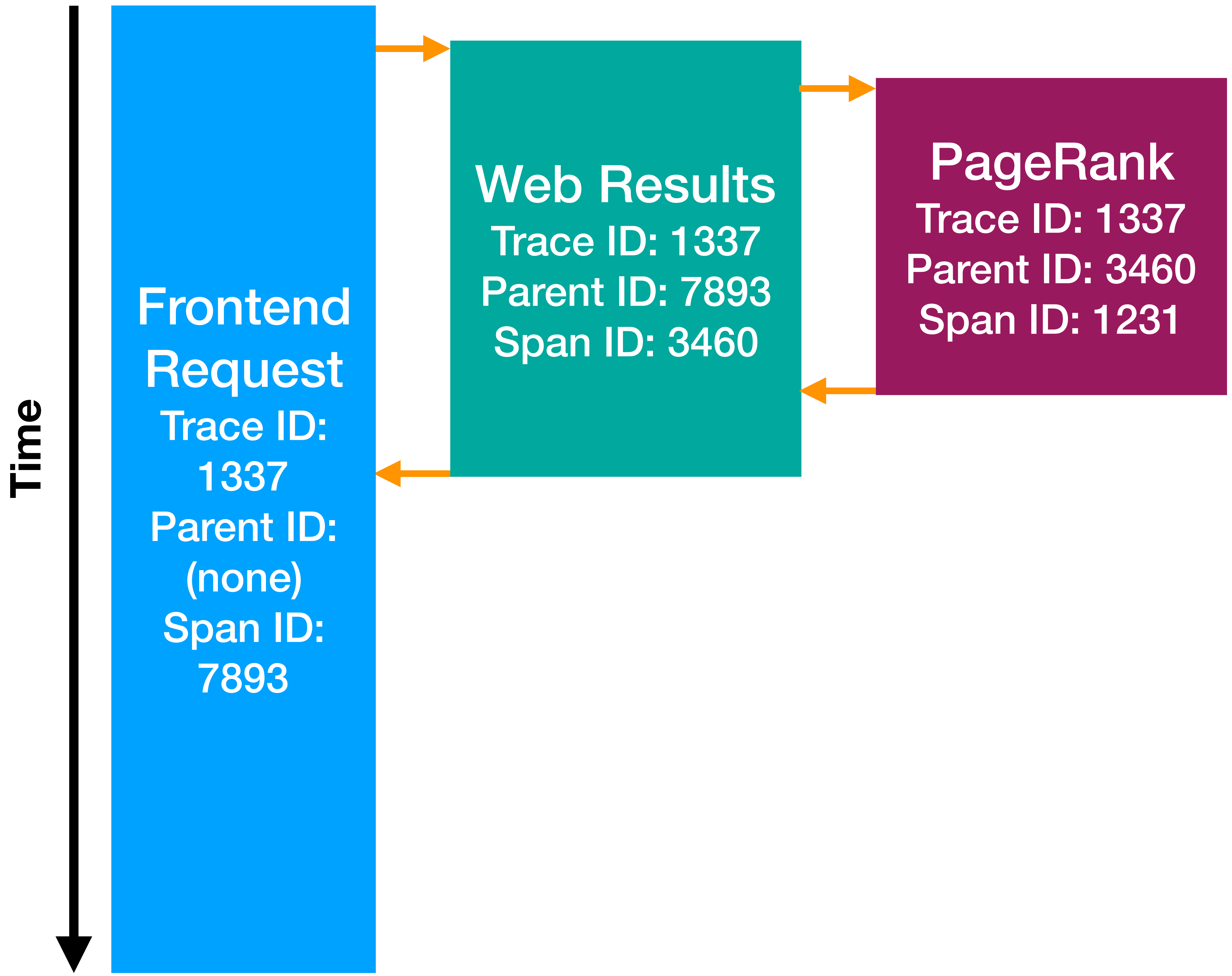

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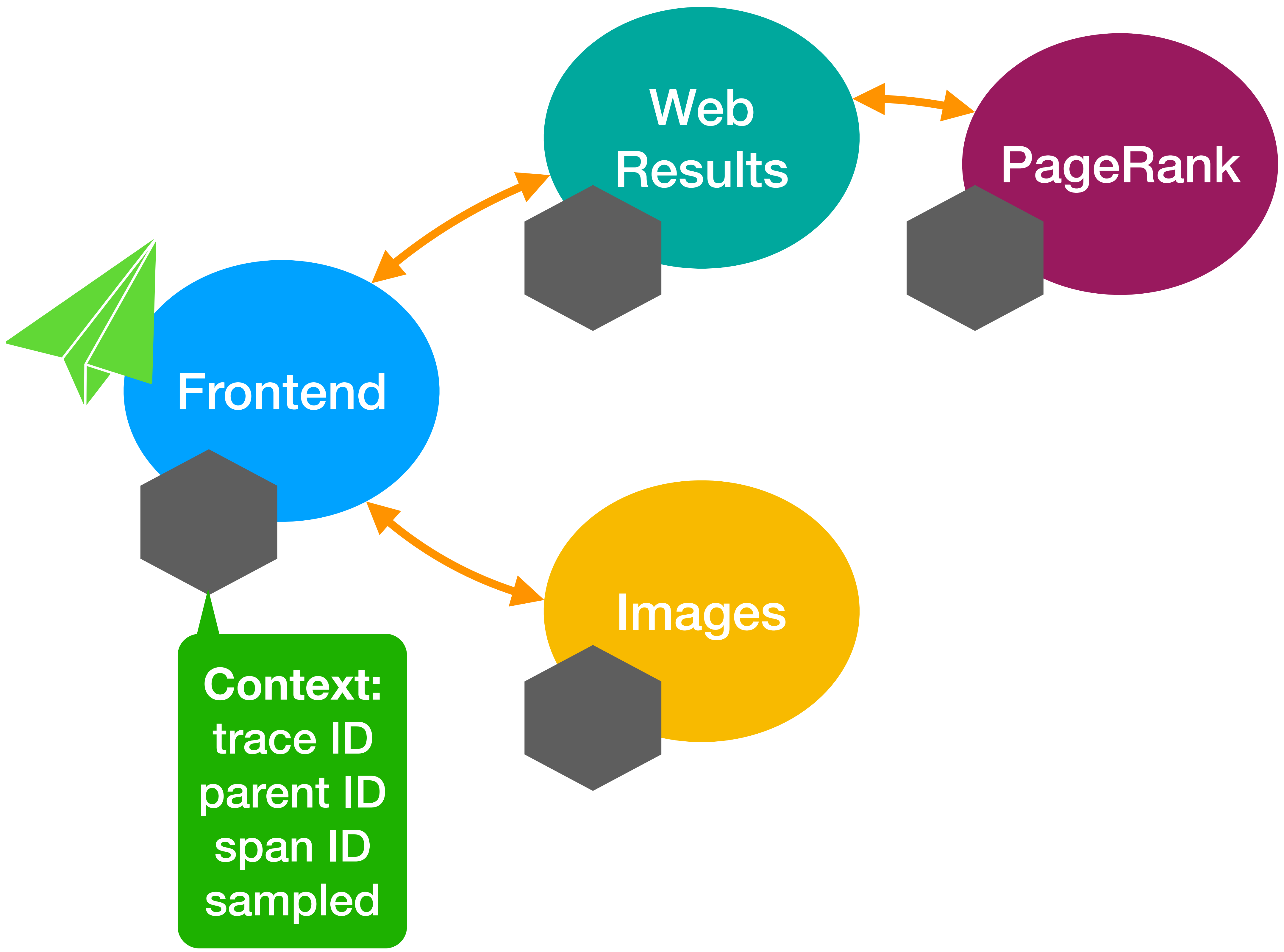

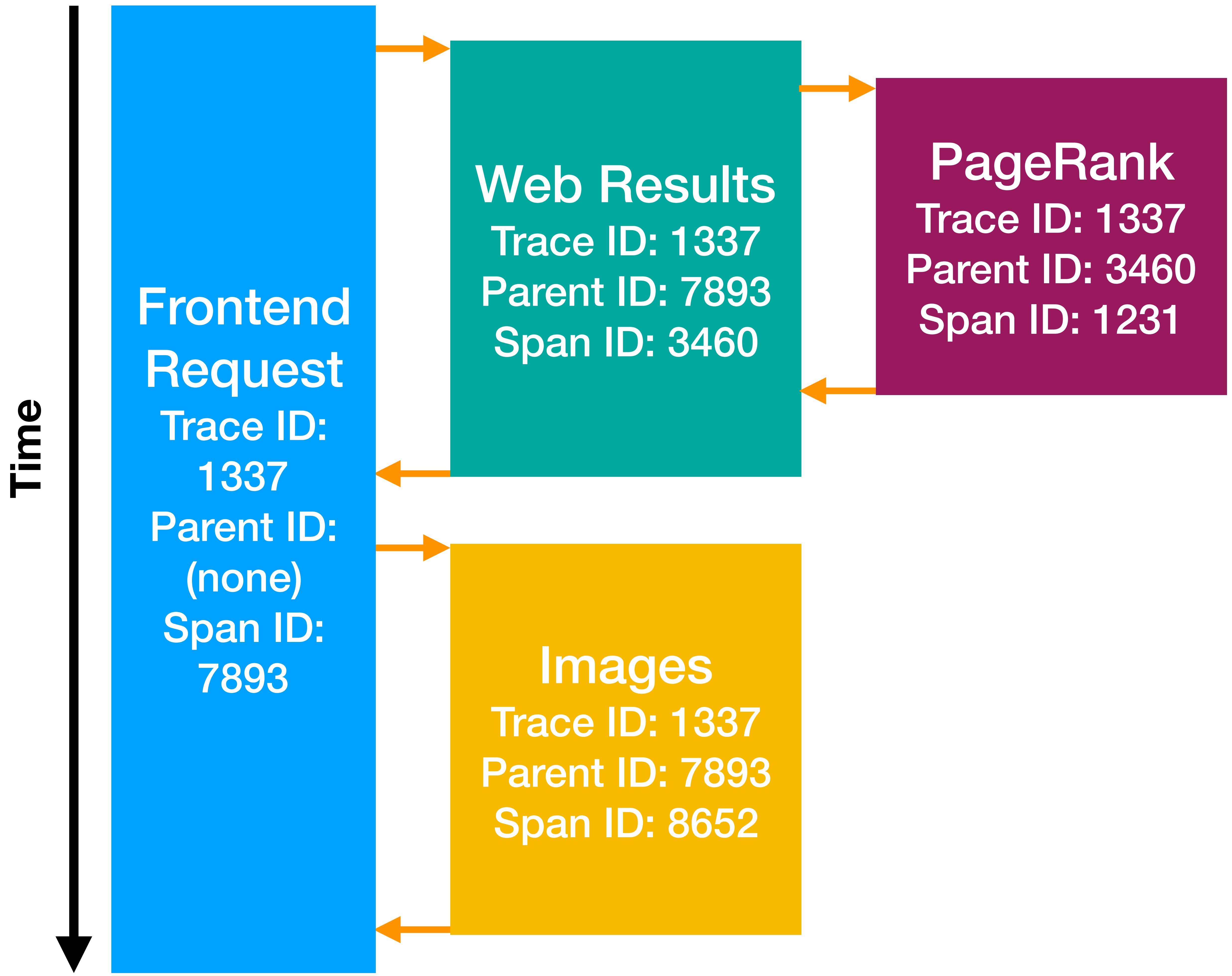

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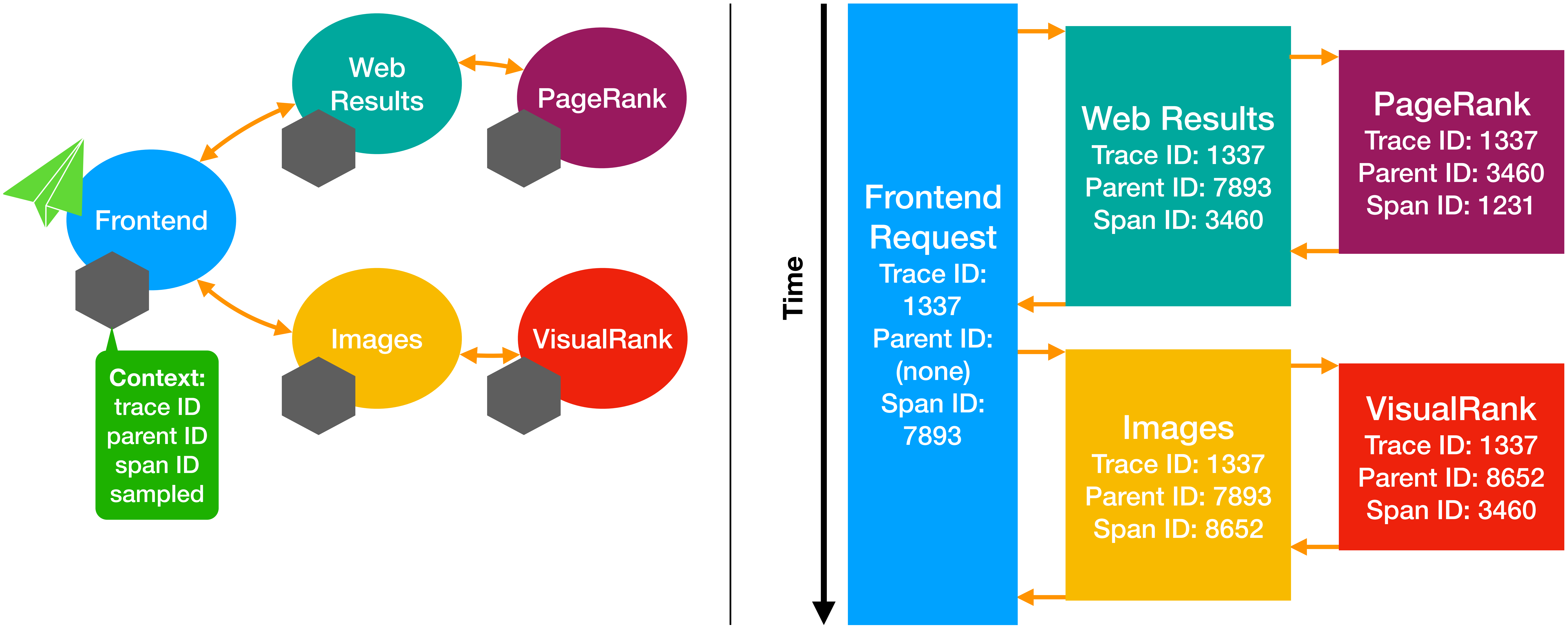

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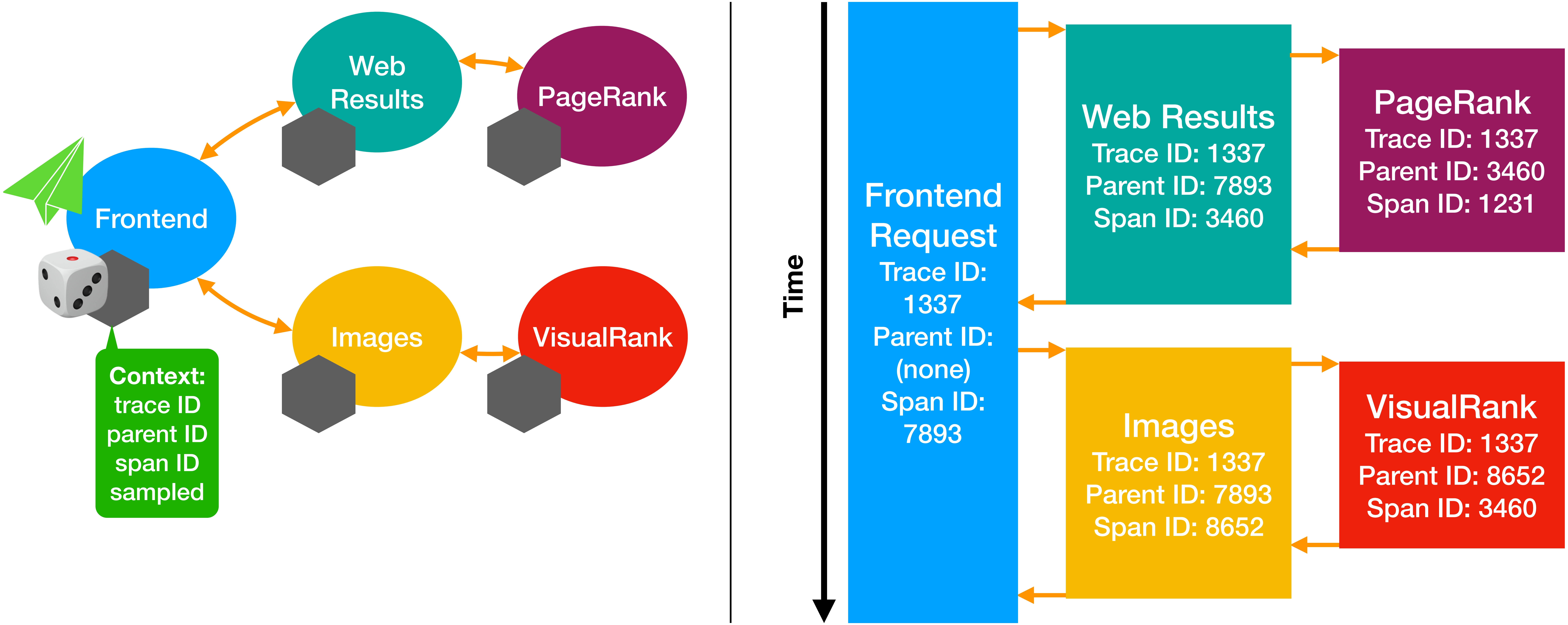

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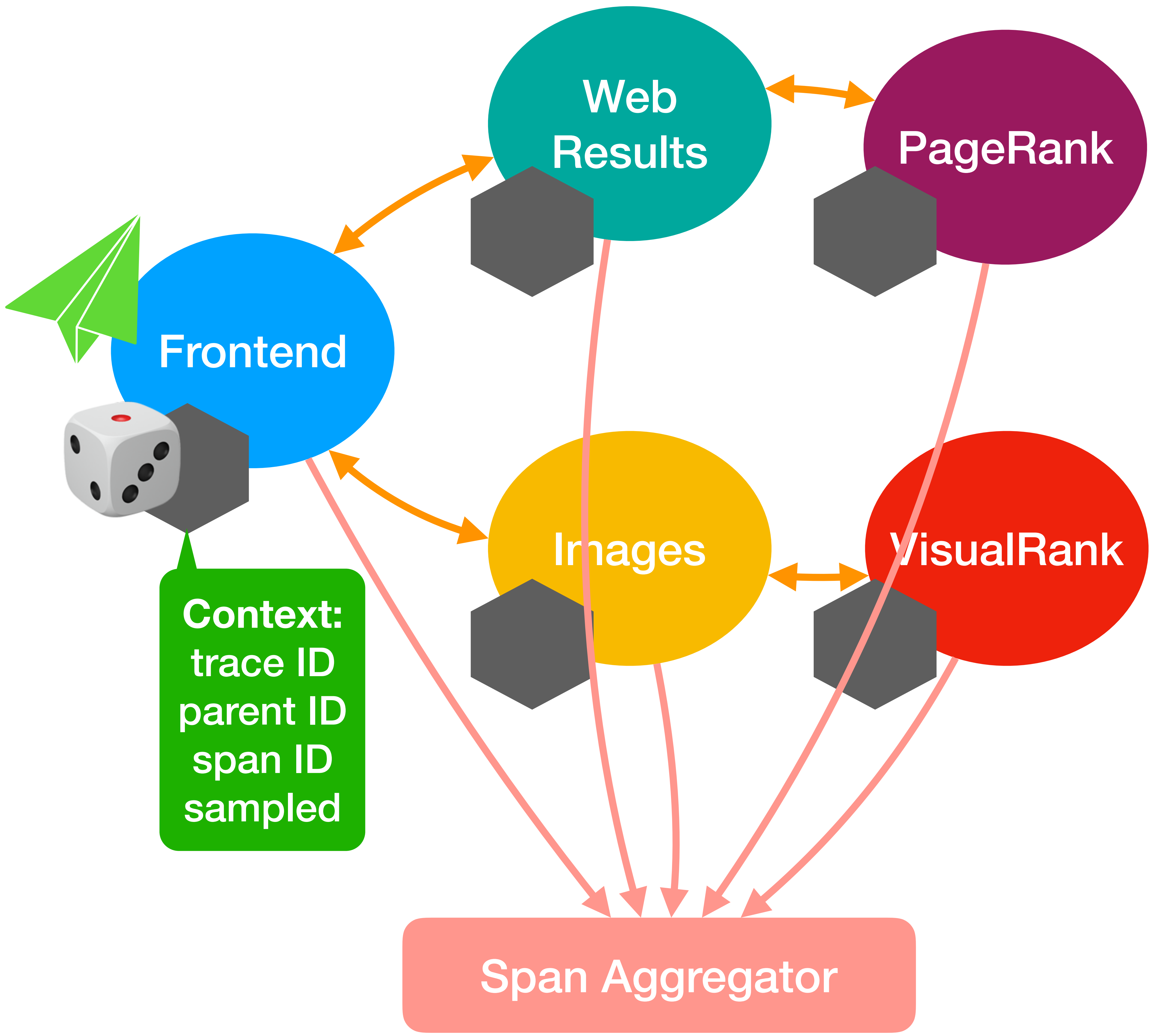
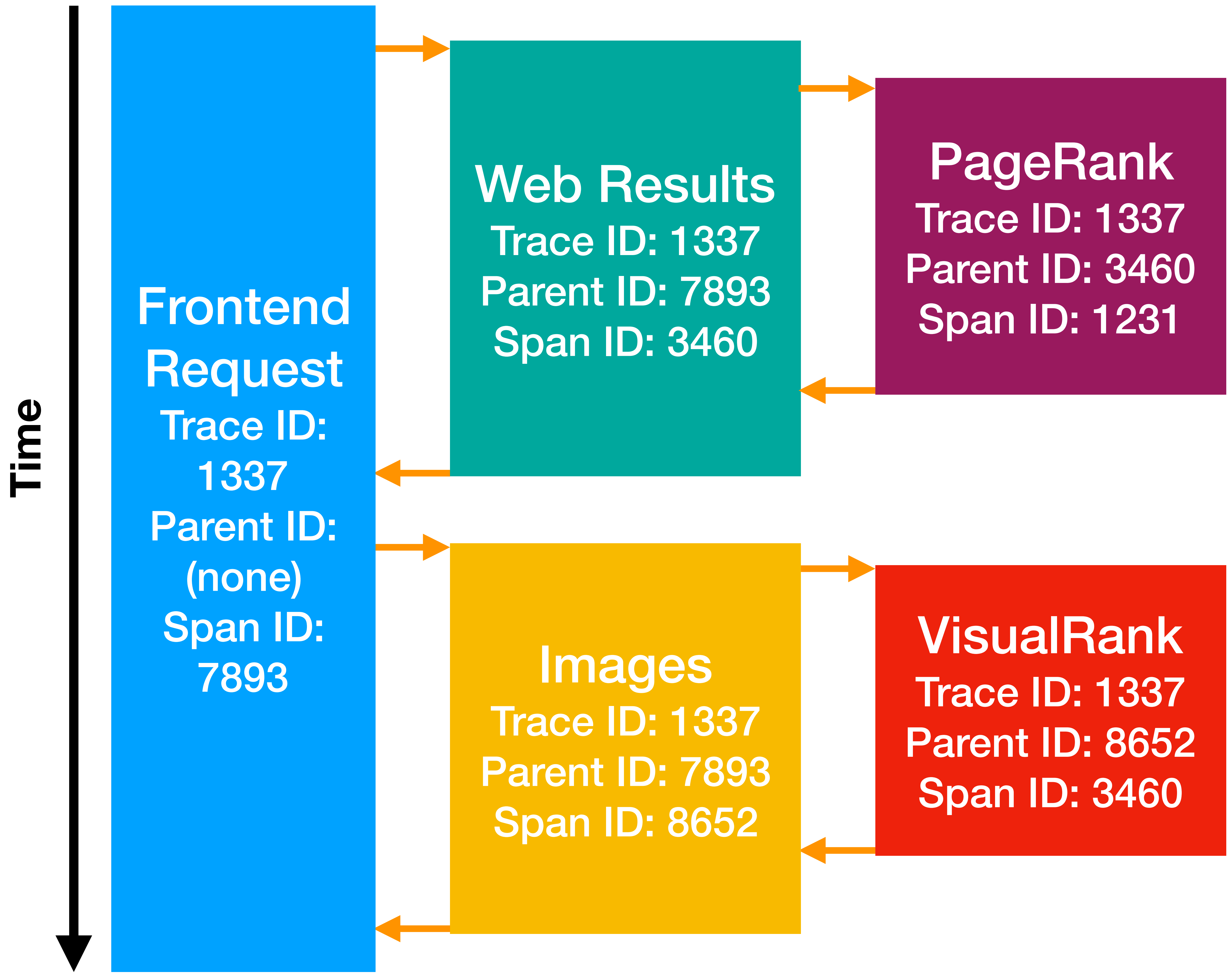
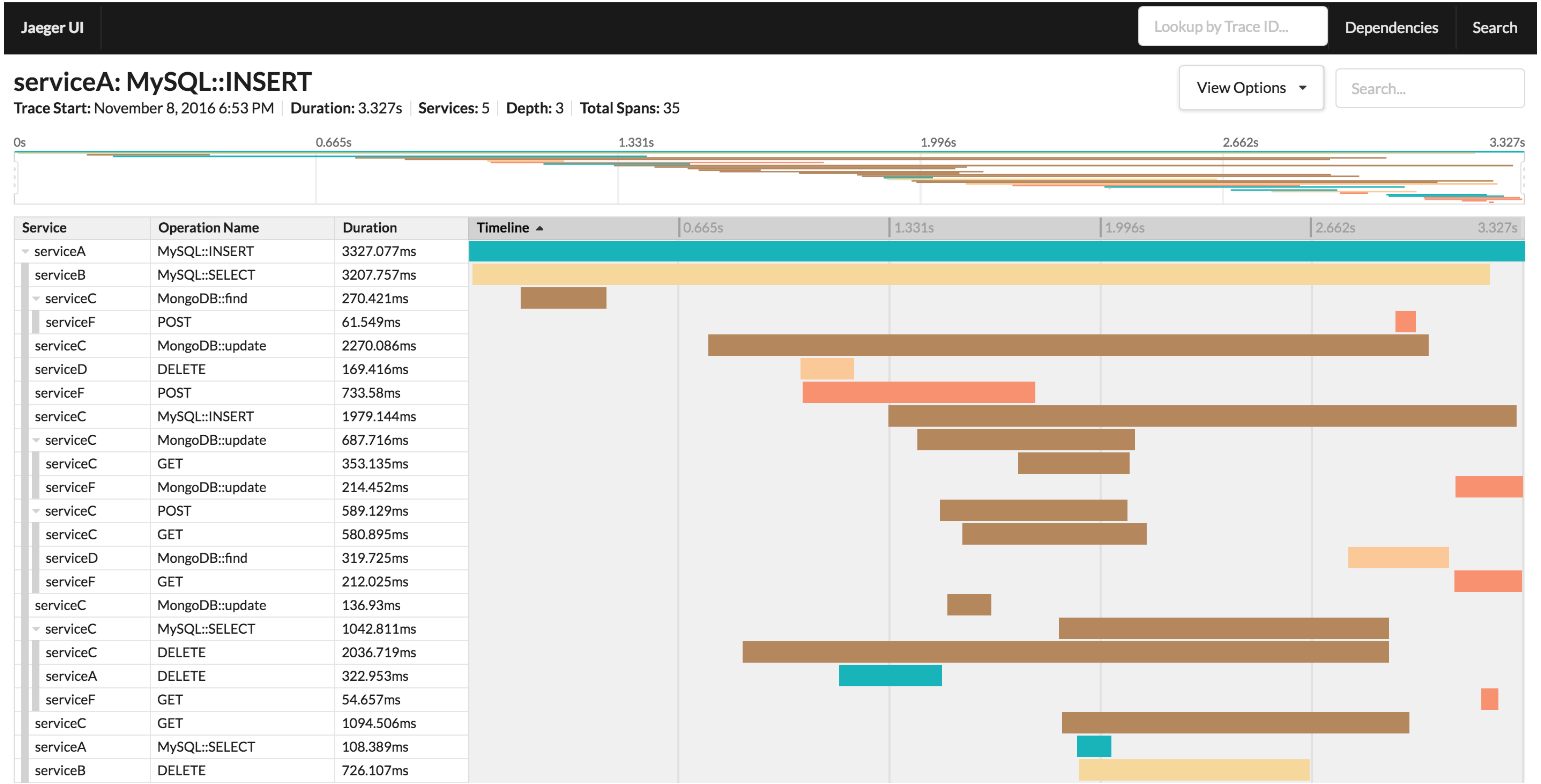


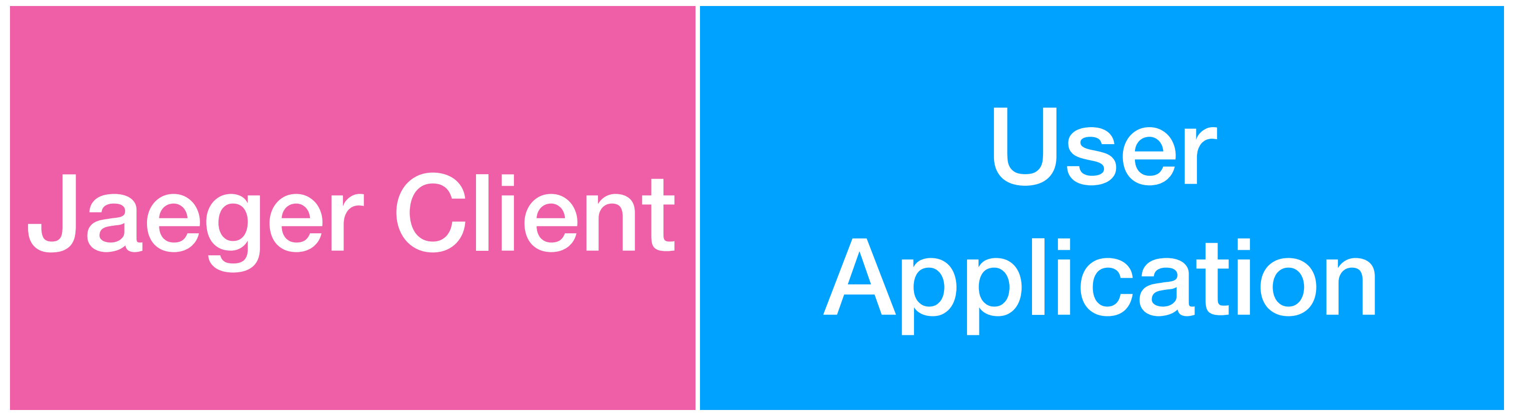


Jaeger



https://eng.uber.com/distributed-tracing/

Skua Design



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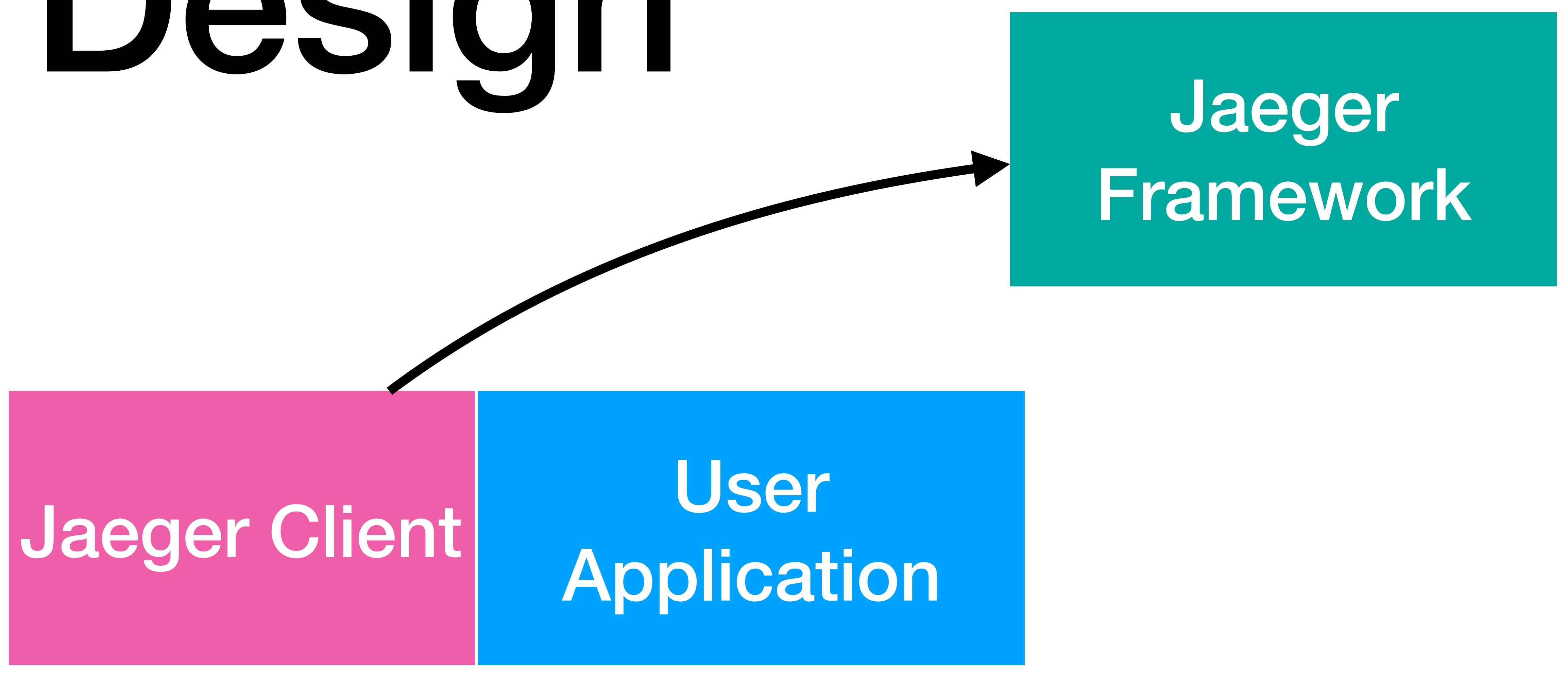

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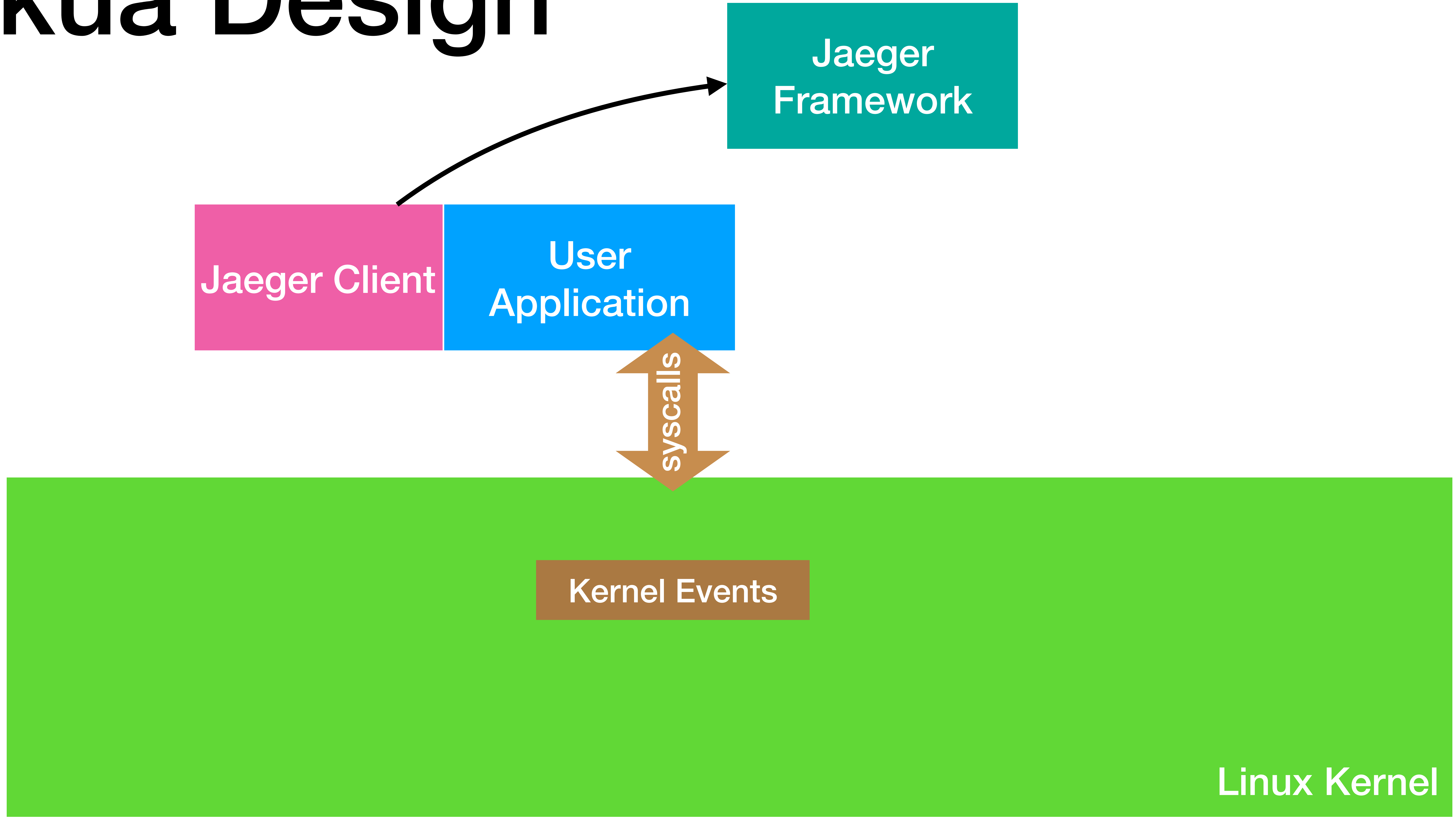
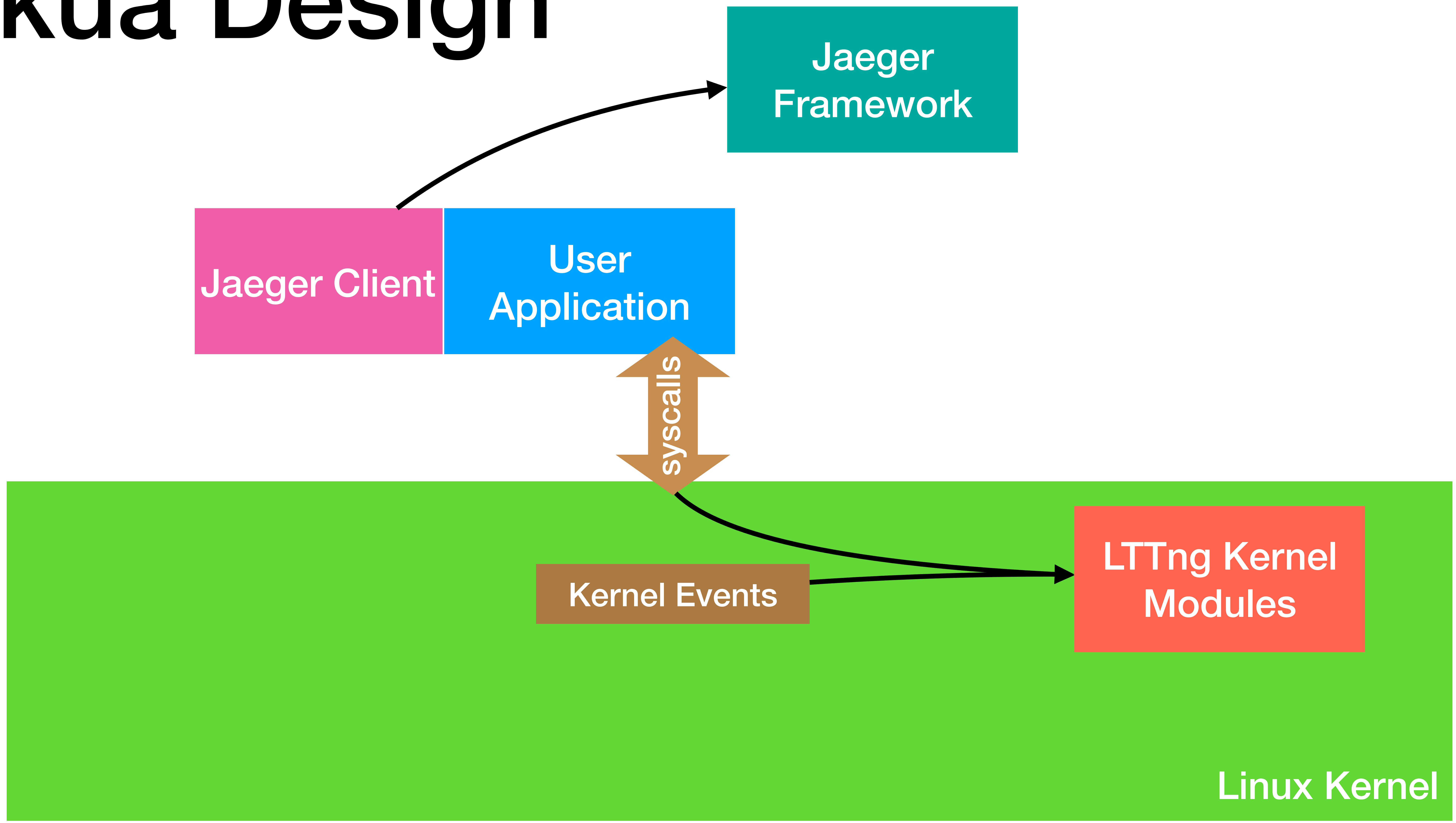

Jaeger Framework
Jaeger Client
User Application
syscalls
Kernel Events
Linux Kernel

Skua Design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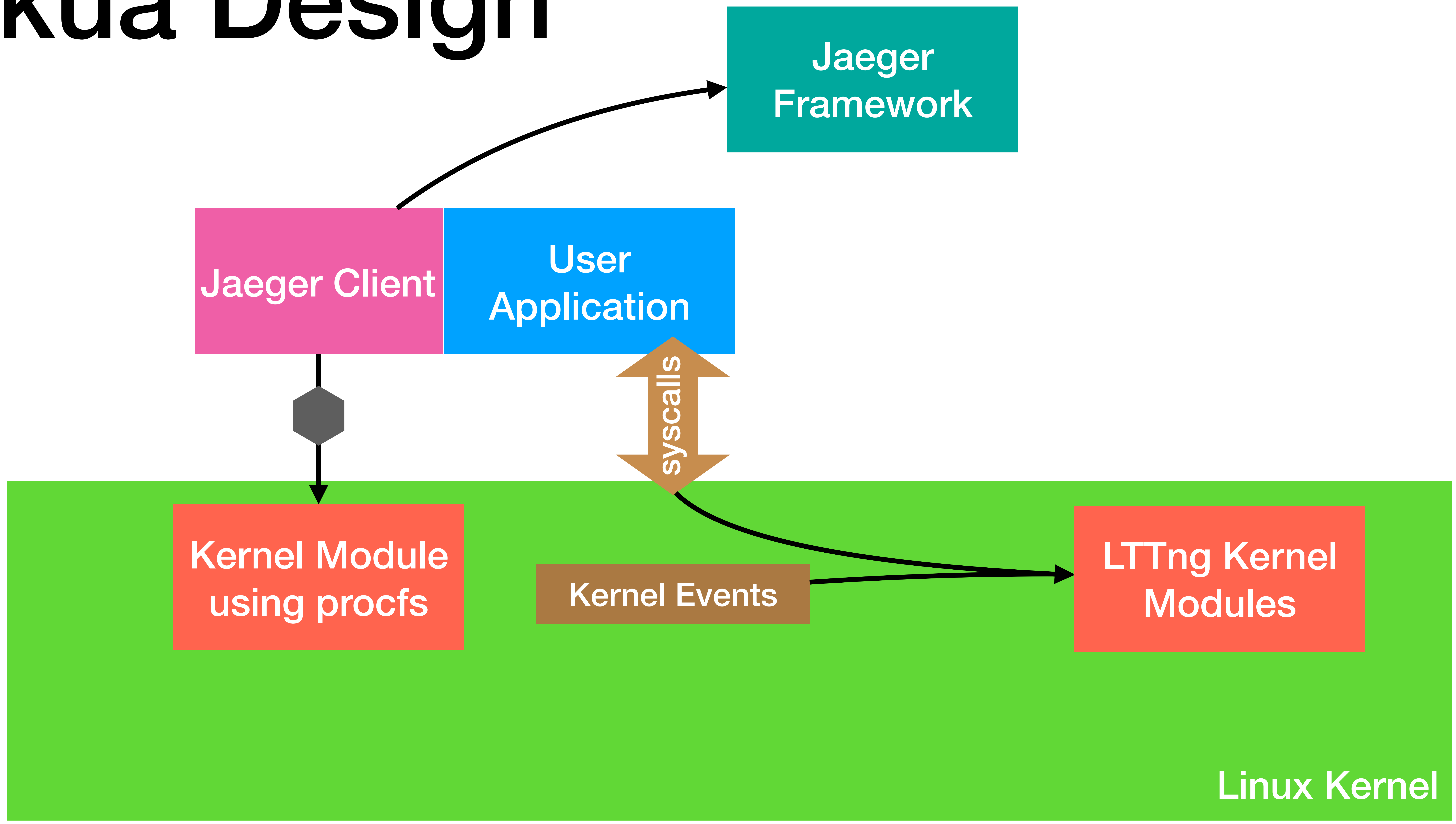
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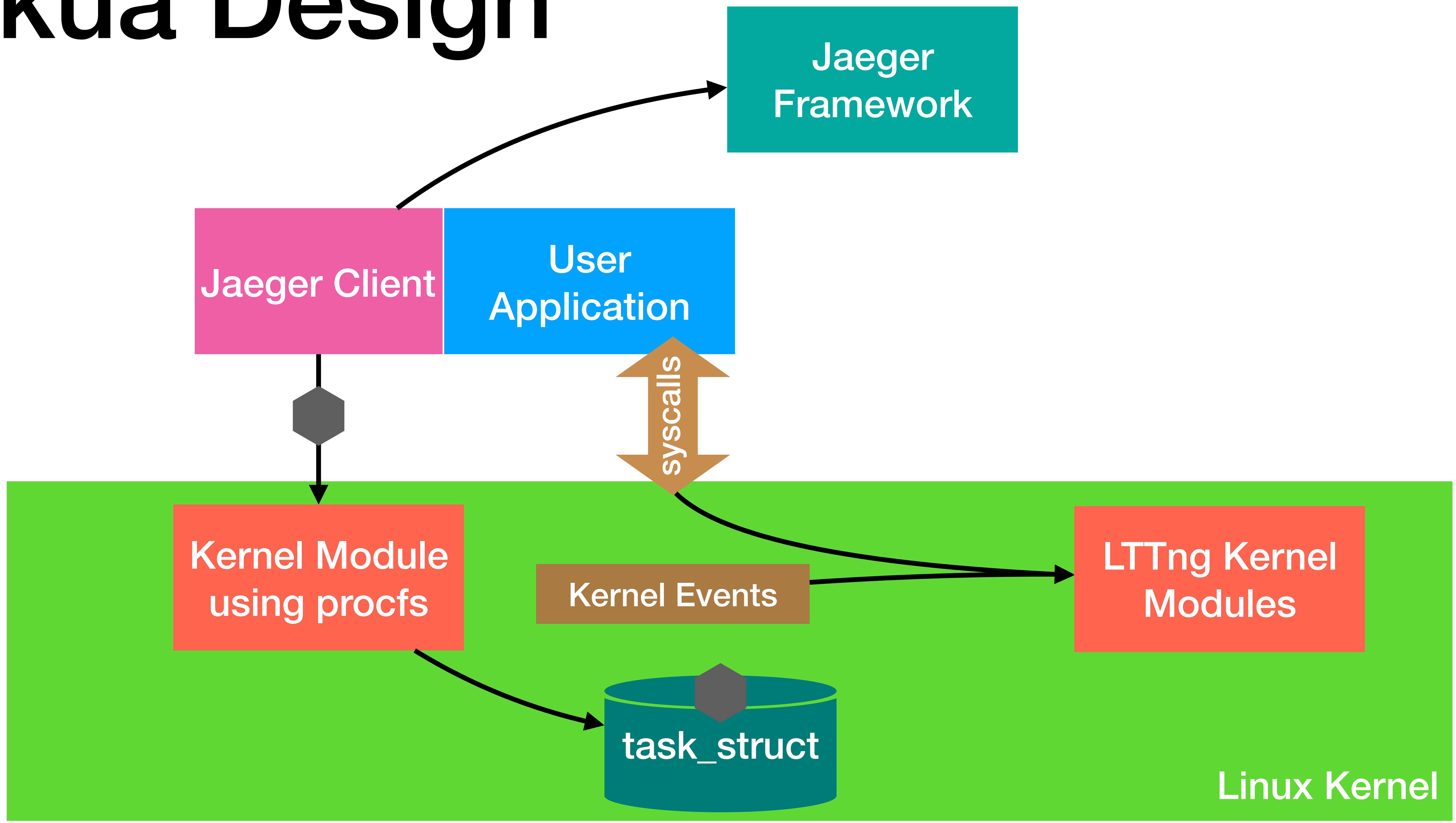
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Kernel Module using procfs
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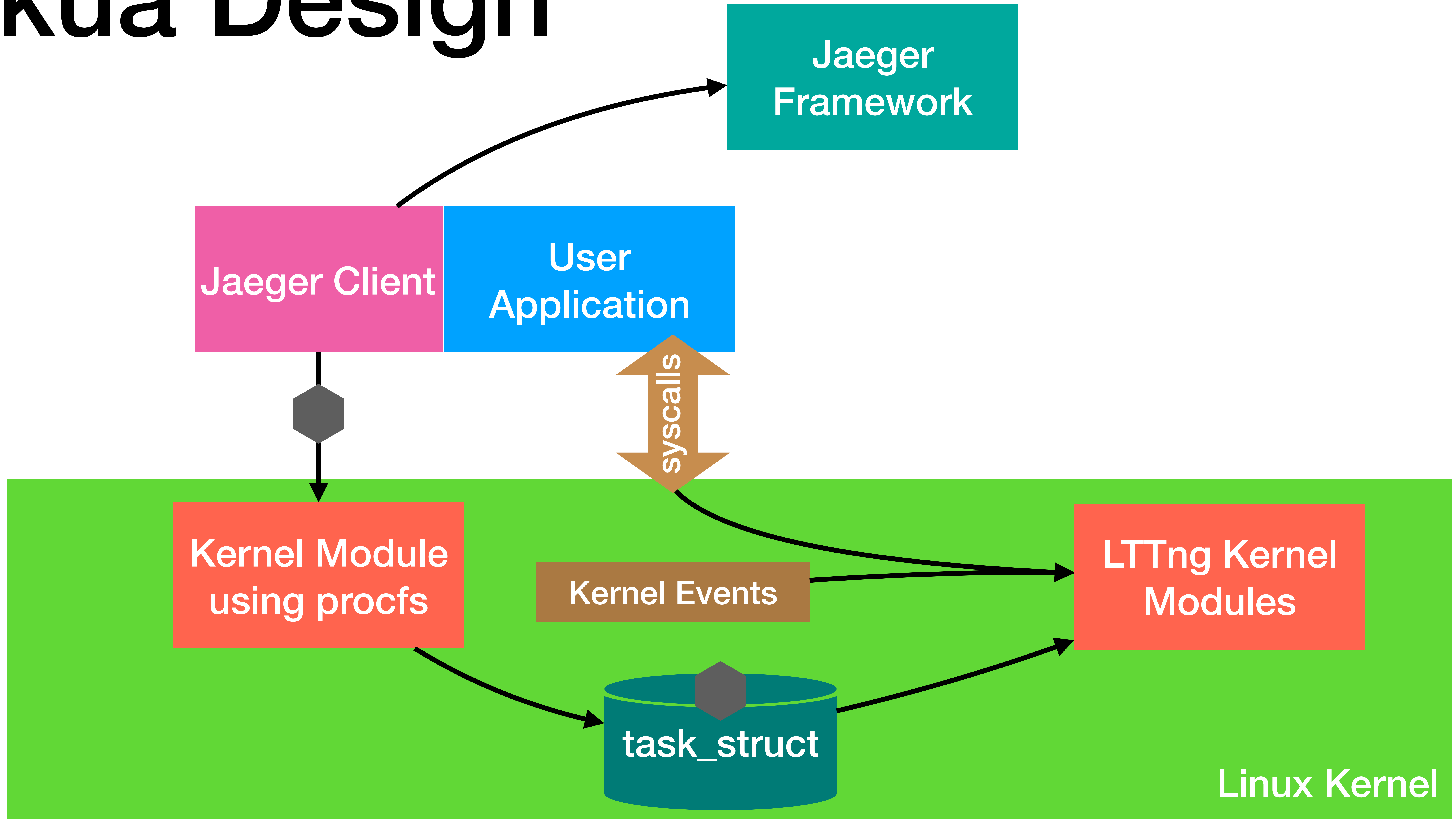
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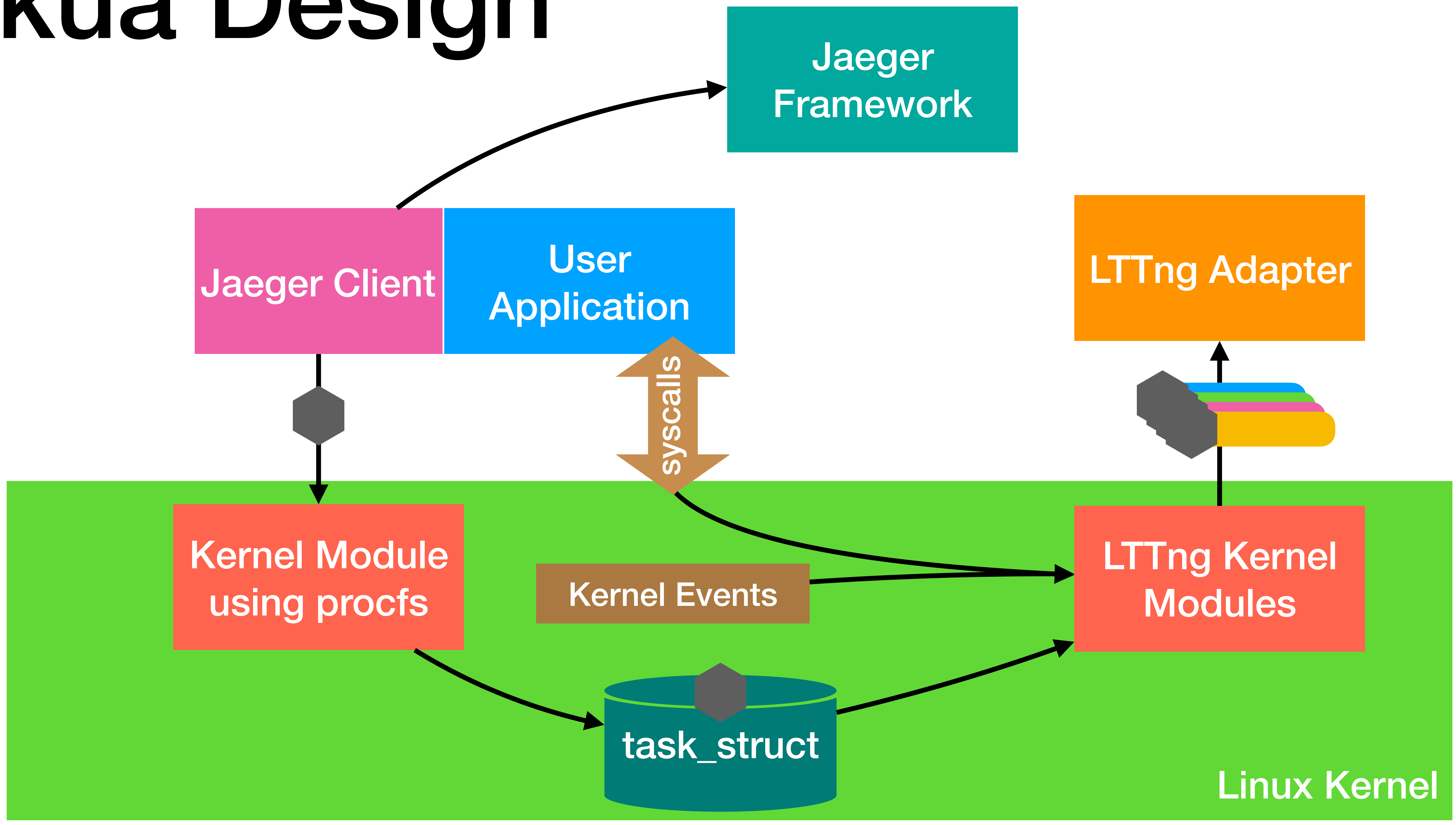
Jaeger Framework
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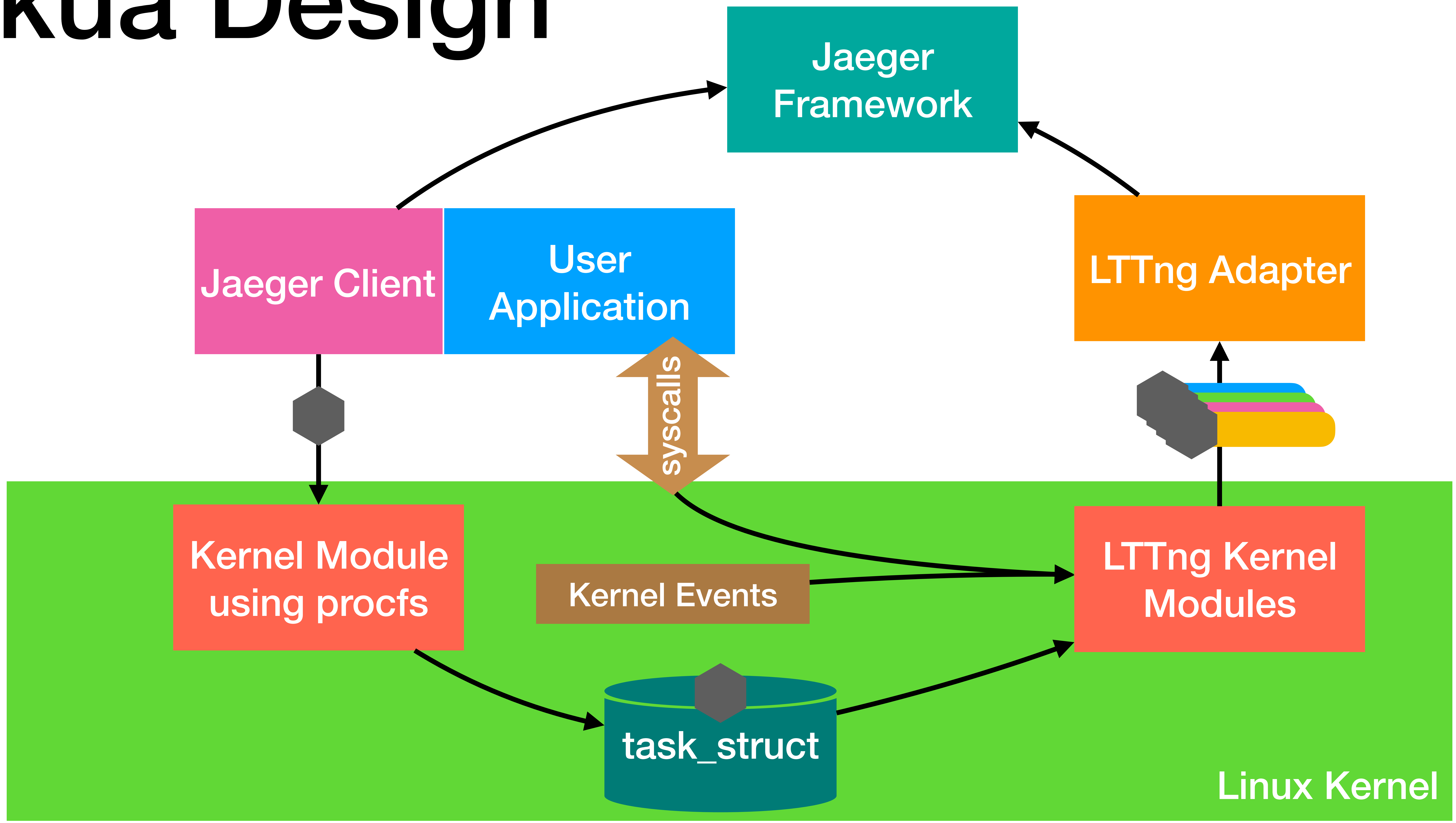

Jaeger Framework
Jaeger Client
User Application
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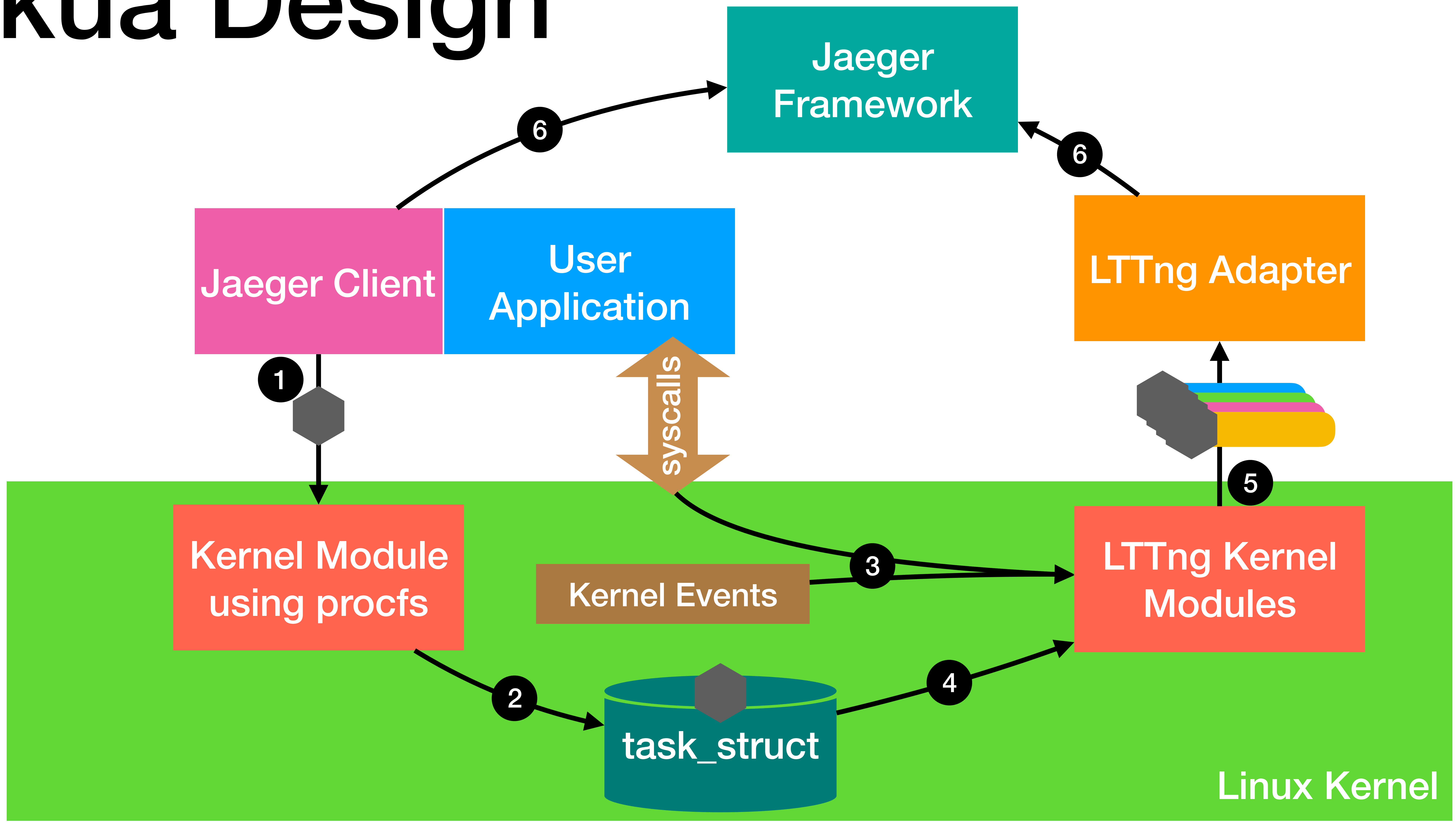
Jaeger Framework
6
6
Jaeger Client
User Application
LTTng Adapter
1
syscalls
5
Kernel Module using procfs
3
Kernel Events
LTTng Kernel Modules
2
4
task_struct
Linux Kernel

Skua Details

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- Treats the Linux kernel as the next level of the span hierarchy
  - Each syscall is considered a span
  - Tracepoint events become span logs
- LTTng kernel modules tag each span and log with the context information **80 LOC**
- Custom adapter sends kernel data into the Jaeger **250 LOC**

Evaluation

Correctness

Setup

- Small C++ program
  - Spawns a few threads
  - Makes 10 different syscalls
- Verifies that Skua is correctly recording syscalls

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Results

- Syscalls recorded in Jaeger as spans
- Misses a few syscalls
  - vDSO — `gettimeofday`
  - LTTng instrumentation
- Tracepoint events recorded properly as logs

Performance Overhead

- Created a small C++ Web server using uWebSockets

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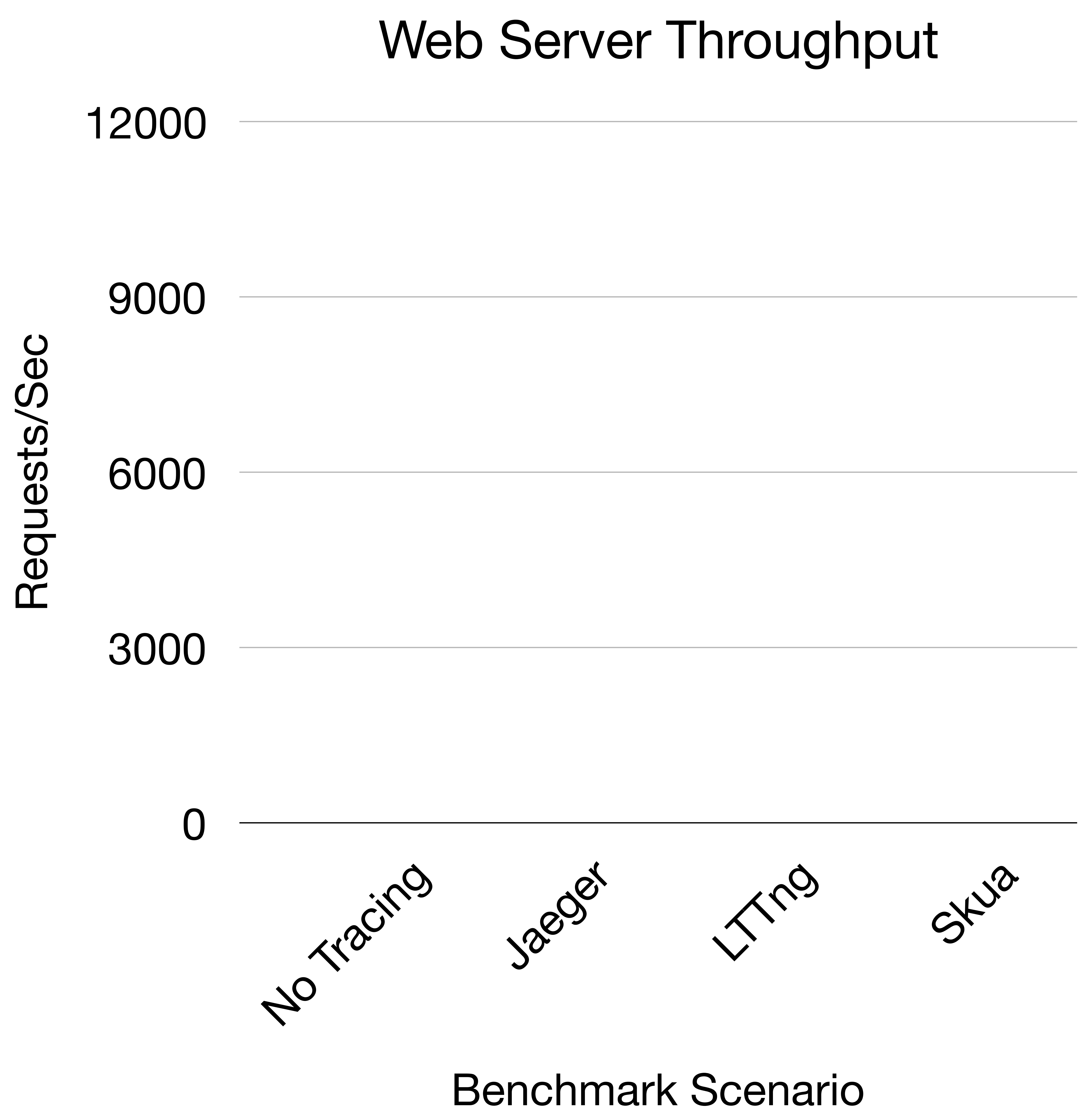
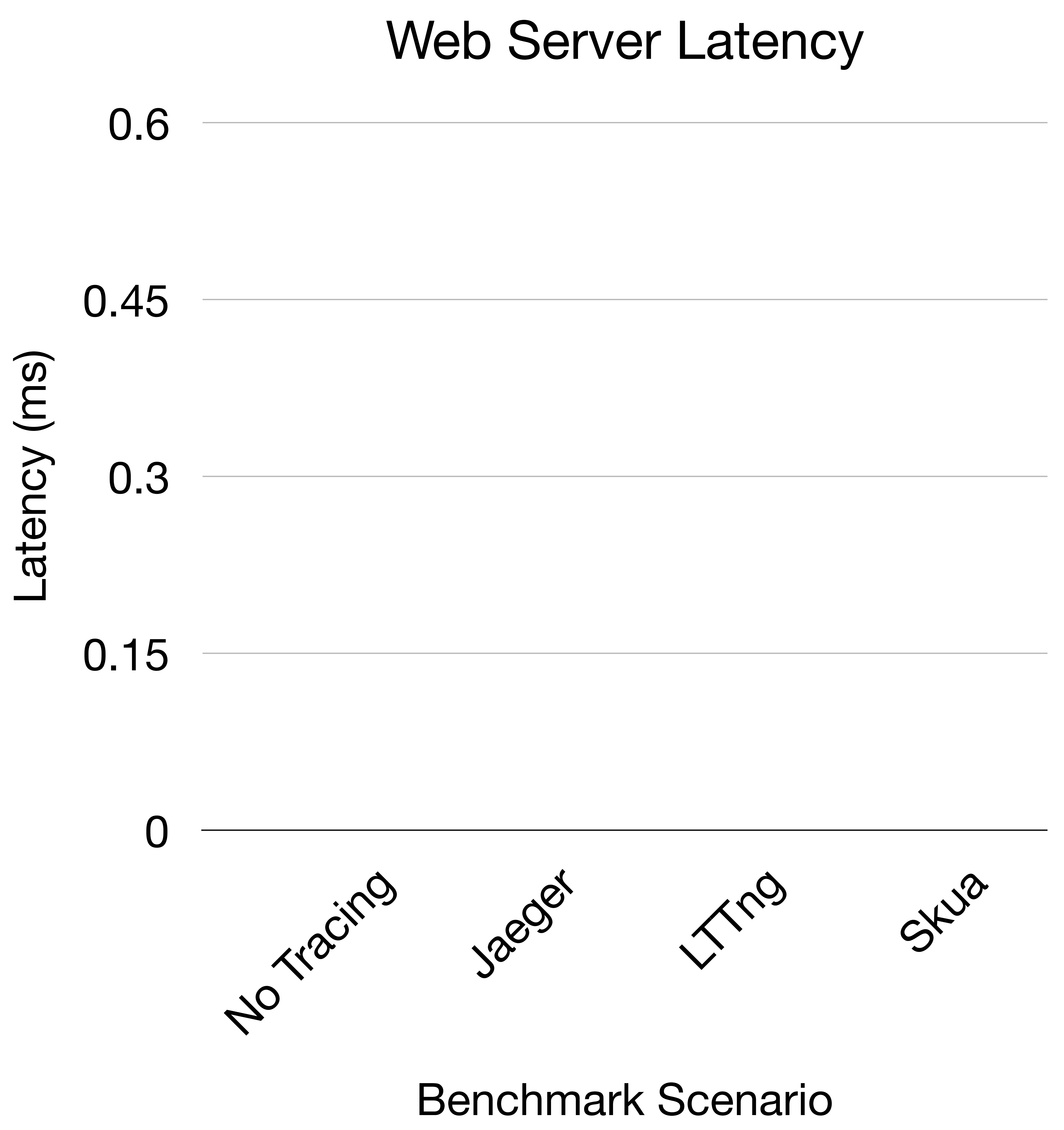
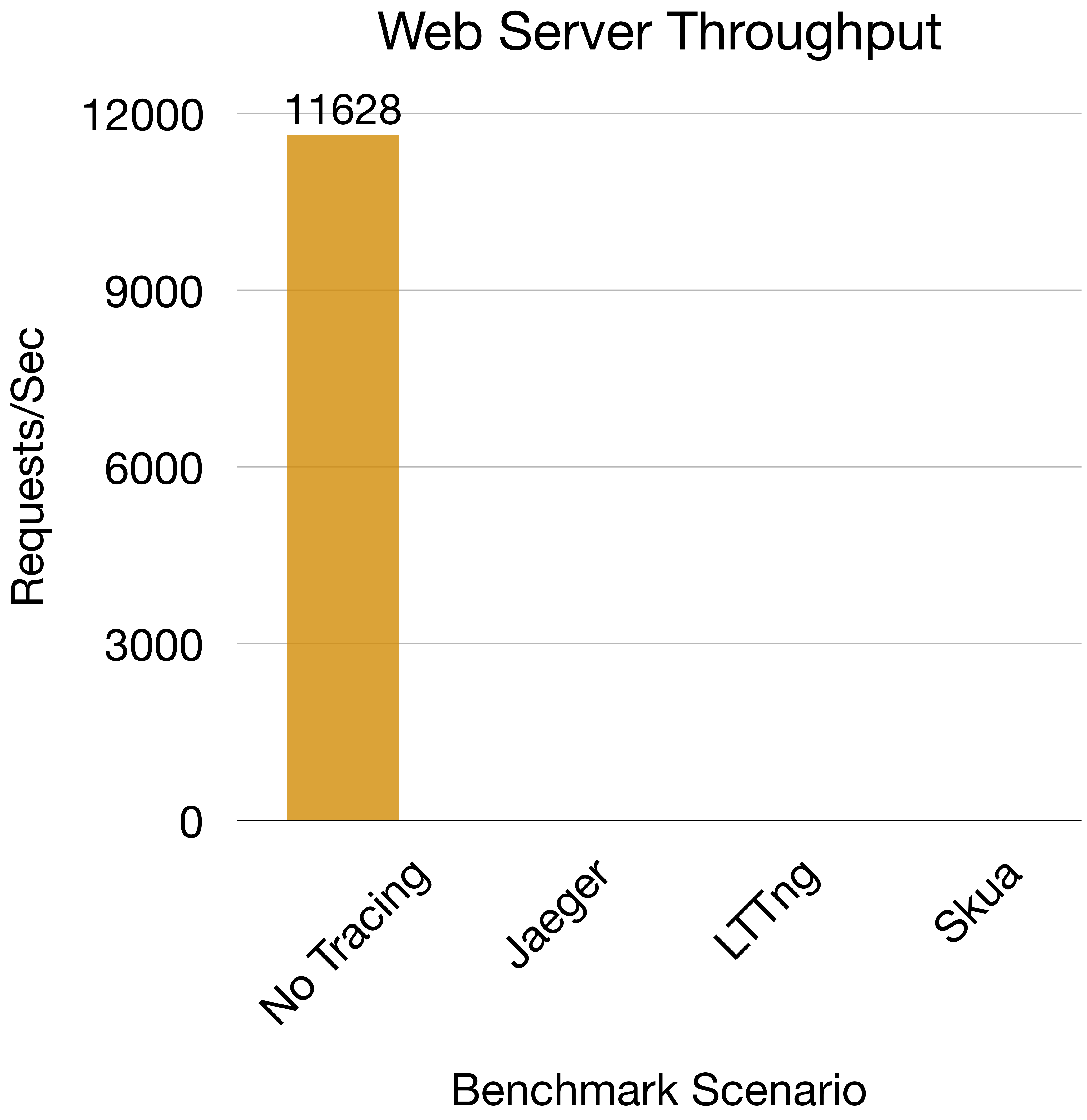
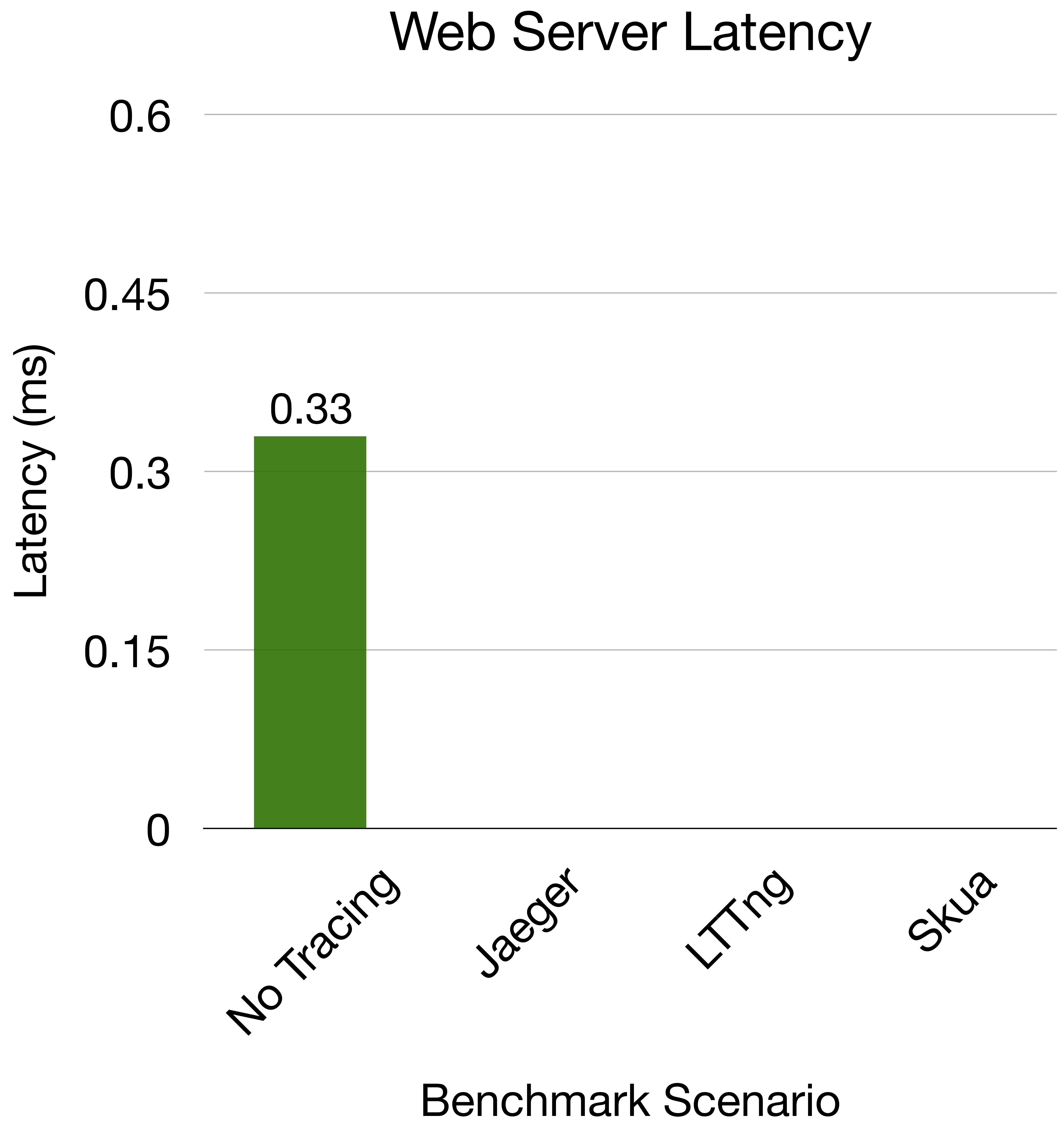
- Used benchmarking tool autocannon
- Evaluated throughput and latency under different tracing scenarios
- 1,000,000 requests, 10 connections
- Traced 0.1% of requests


Web Server Throughput
12000
9000
6000
3000
0
Requests/Sec
No Tracing
Jaeger
LTTng
Skua
Benchmark Scenario


Web Server Latency
0.6
0.45
0.3
0.15
0
Latency (ms)
No Tracing
Jaeger
LTTng
Skua
Benchmark Scenario


Web Server Throughput
11628
12000
9000
6000
3000
0
Requests/Sec
No Tracing
Jaeger
LTTng
Skua
Benchmark Scenario


Web Server Latency
0.6
0.45
0.33
0.3
0.15
0
Latency (ms)
No Tracing
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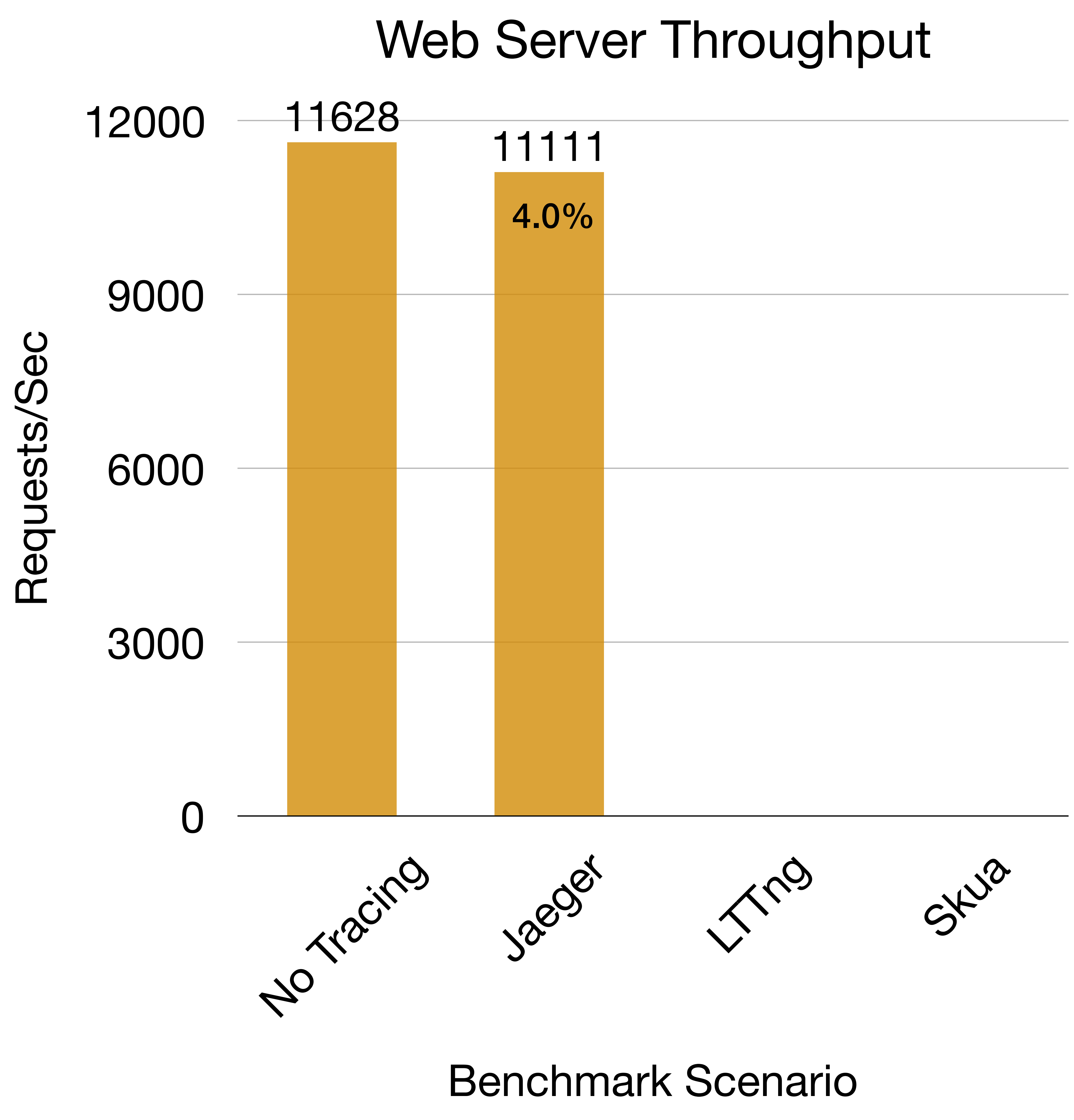
Web Server Throughput
12000
9000
6000
3000
0
Requests/Sec
11628
11111
4.0%
No Tracing
Jaeger
LTTng
Skua
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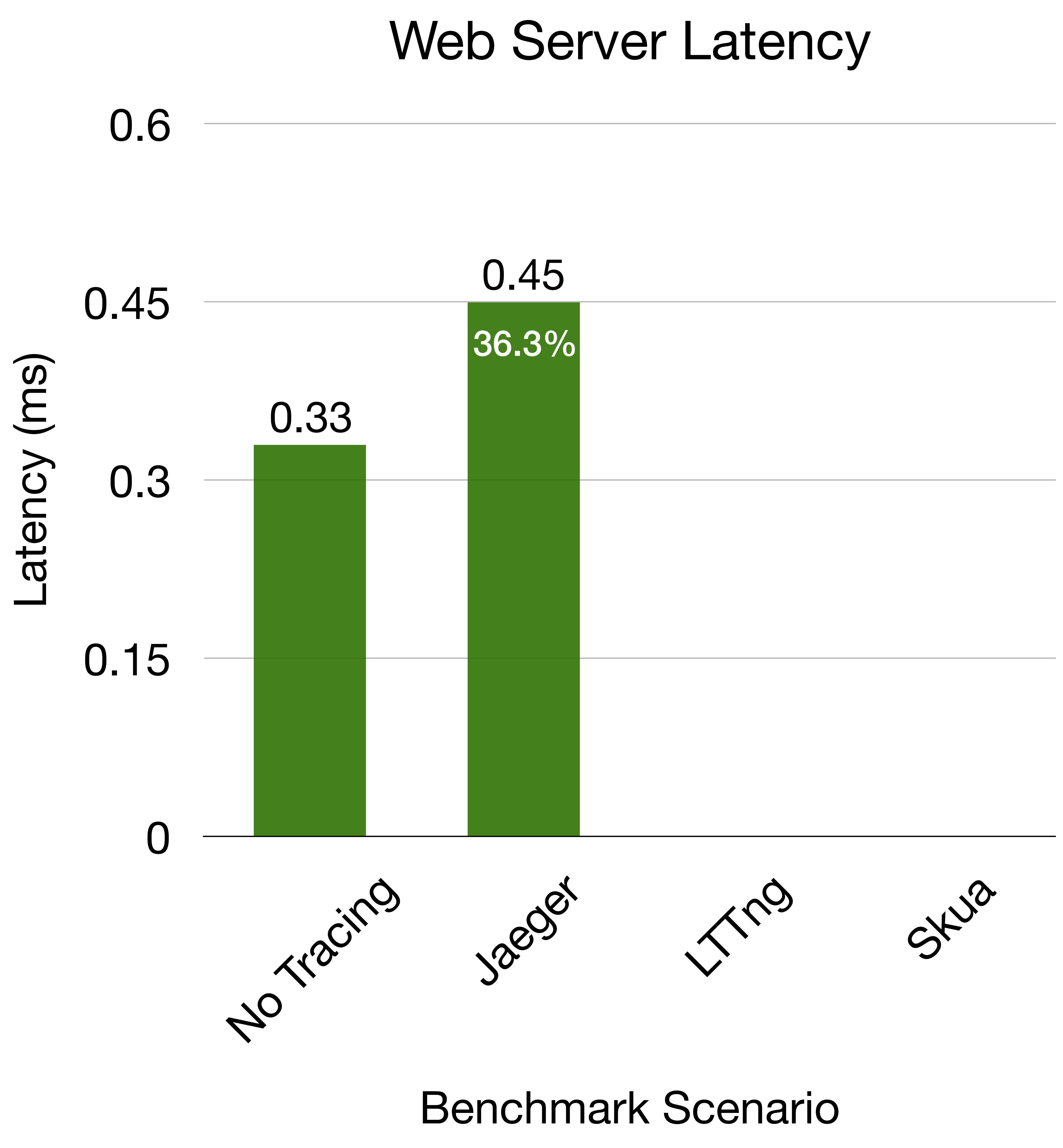
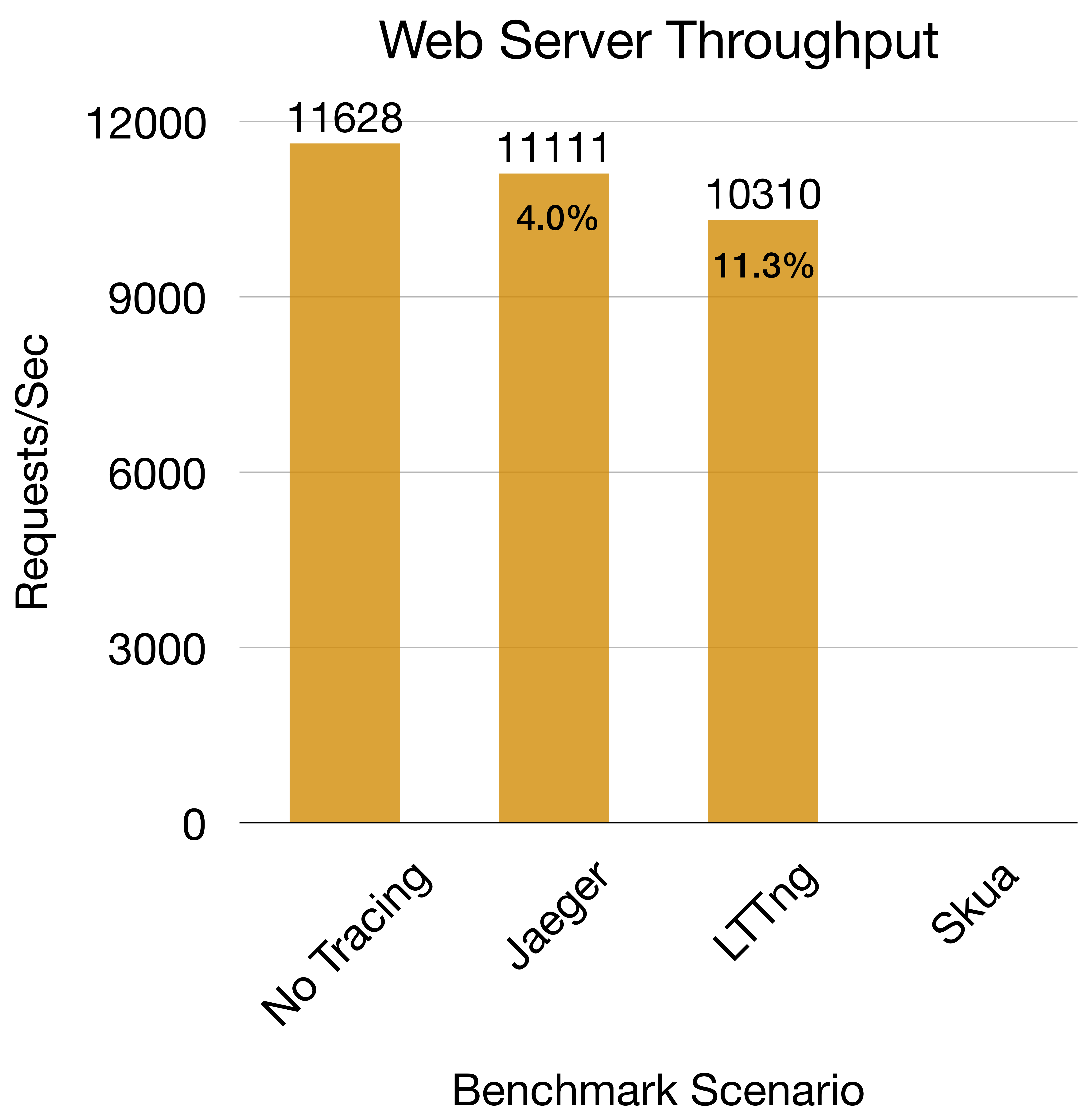
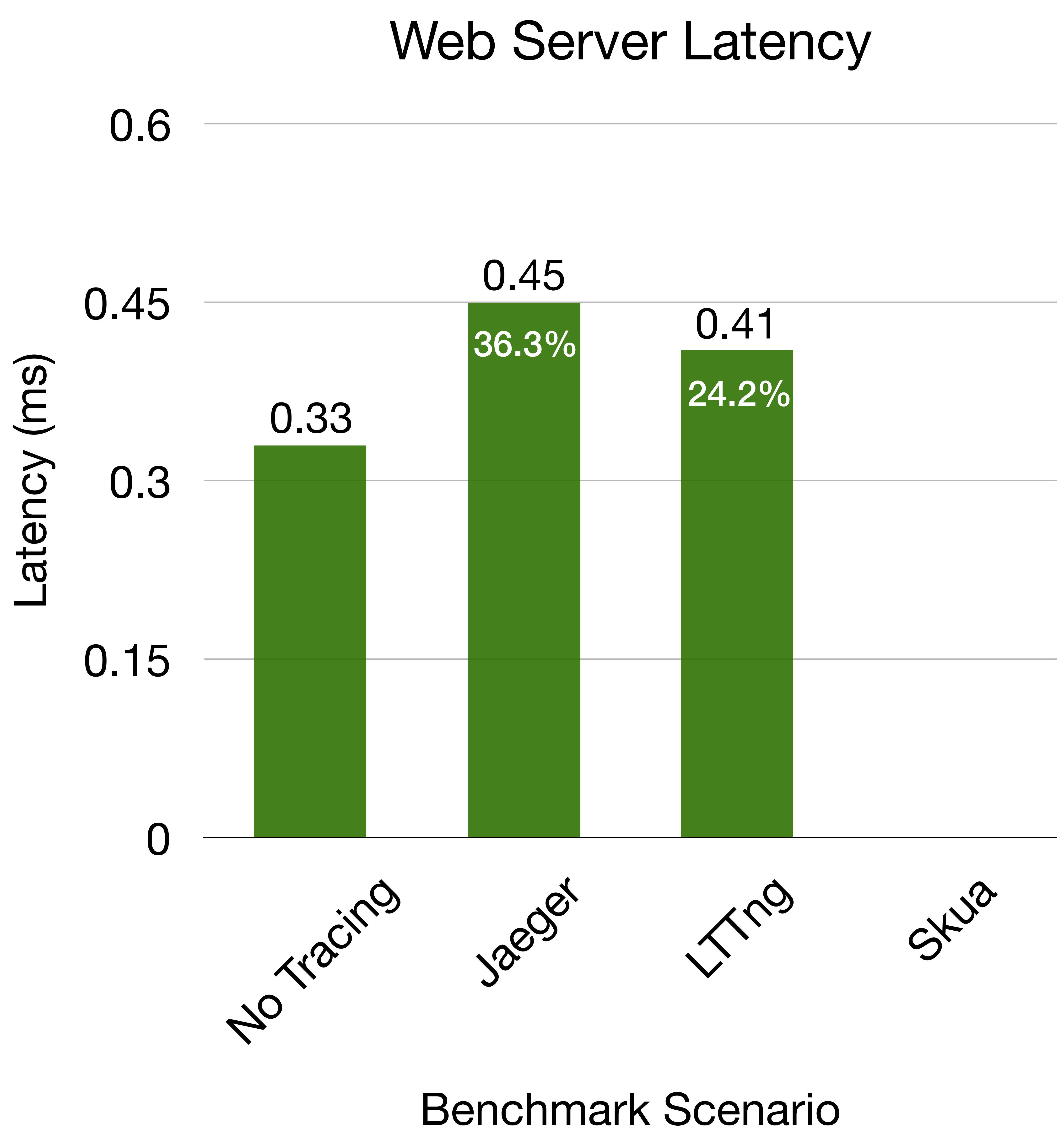
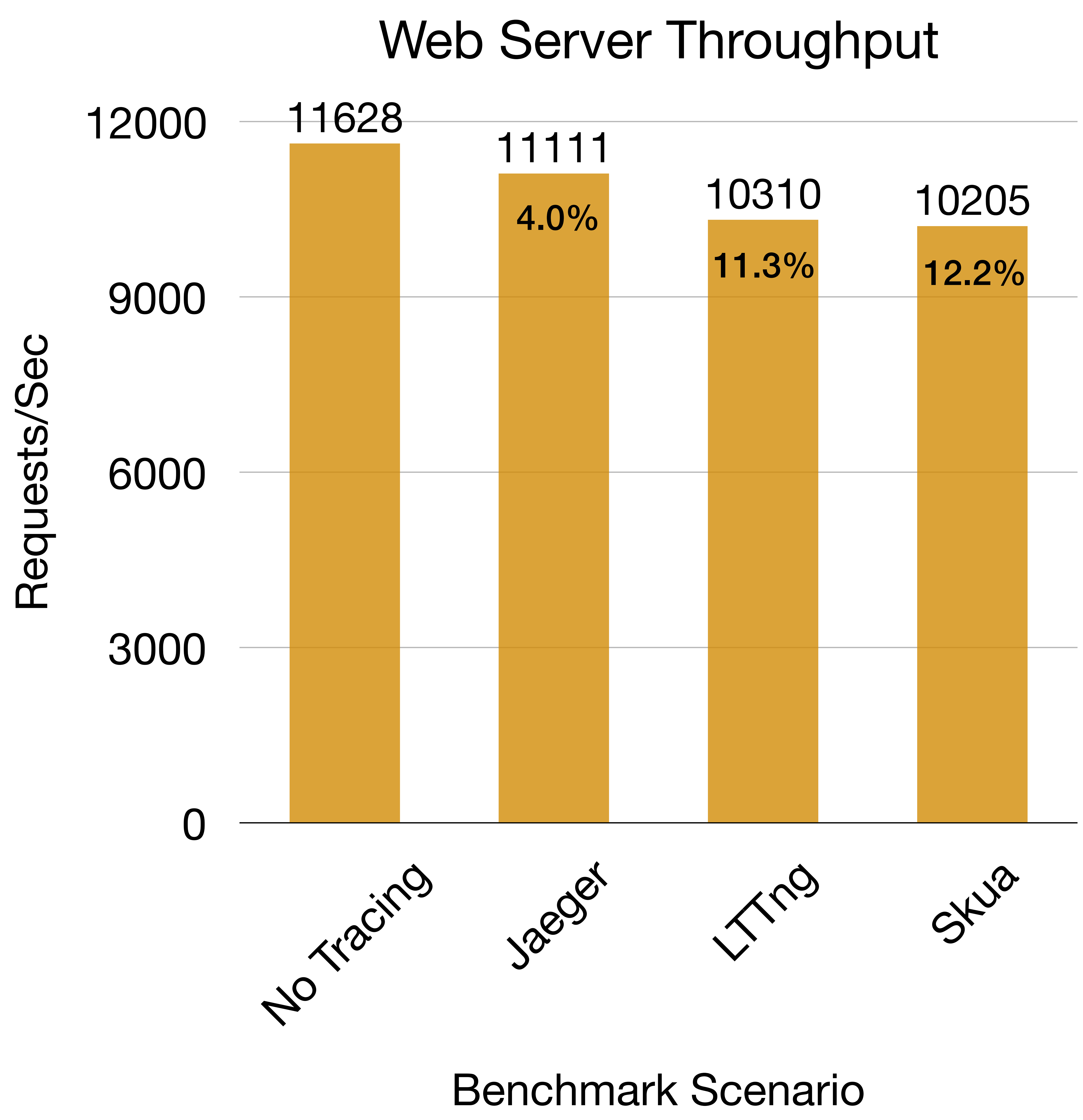

Web Server Latency
0.6
0.45
0.3
0.15
0
Latency (ms)
0.33
0.45
36.3%
No Tracing
Jaeger
LTTng
Skua
Benchmark Scenario


Web Server Throughput
Requests/Sec
12000
9000
6000
3000
0
11628
11111
4.0%
10310
11.3%
No Tracing
Jaeger
LTTng
Skua
Benchmark Scenario


Web Server Latency
Latency (ms)
0.6
0.45
0.3
0.15
0
0.33
0.45
36.3%
0.41
24.2%
No Tracing
Jaeger
LTTng
Skua
Benchmark Scenario


Web Server Throughput
12000
9000
6000
3000
0
Requests/Sec
11628
11111
4.0%
10310
11.3%
10205
12.2%
No Tracing
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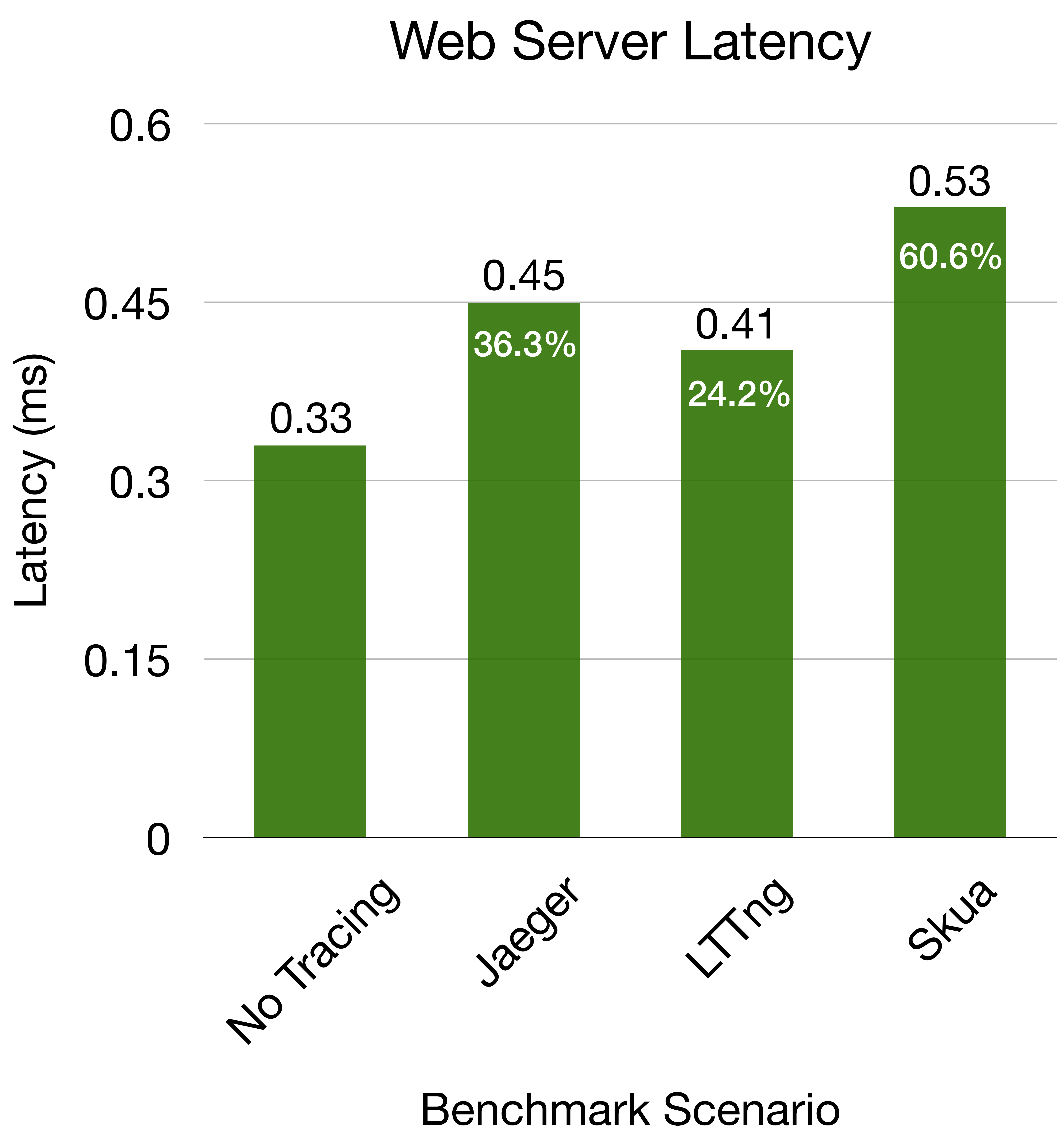
Web Server Latency
0.6
0.45
0.3
0.15
0
Latency (ms)
0.33
0.45
36.3%
0.41
24.2%
0.53
60.6%
No Tracing
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Conclusions

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Conclusions

- Can use distributed tracing to monitor and debug complex distributed systems
- Current open source distributed tracing frameworks miss kernel information
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https://github.com/SkuaTracing

Acknowledgements

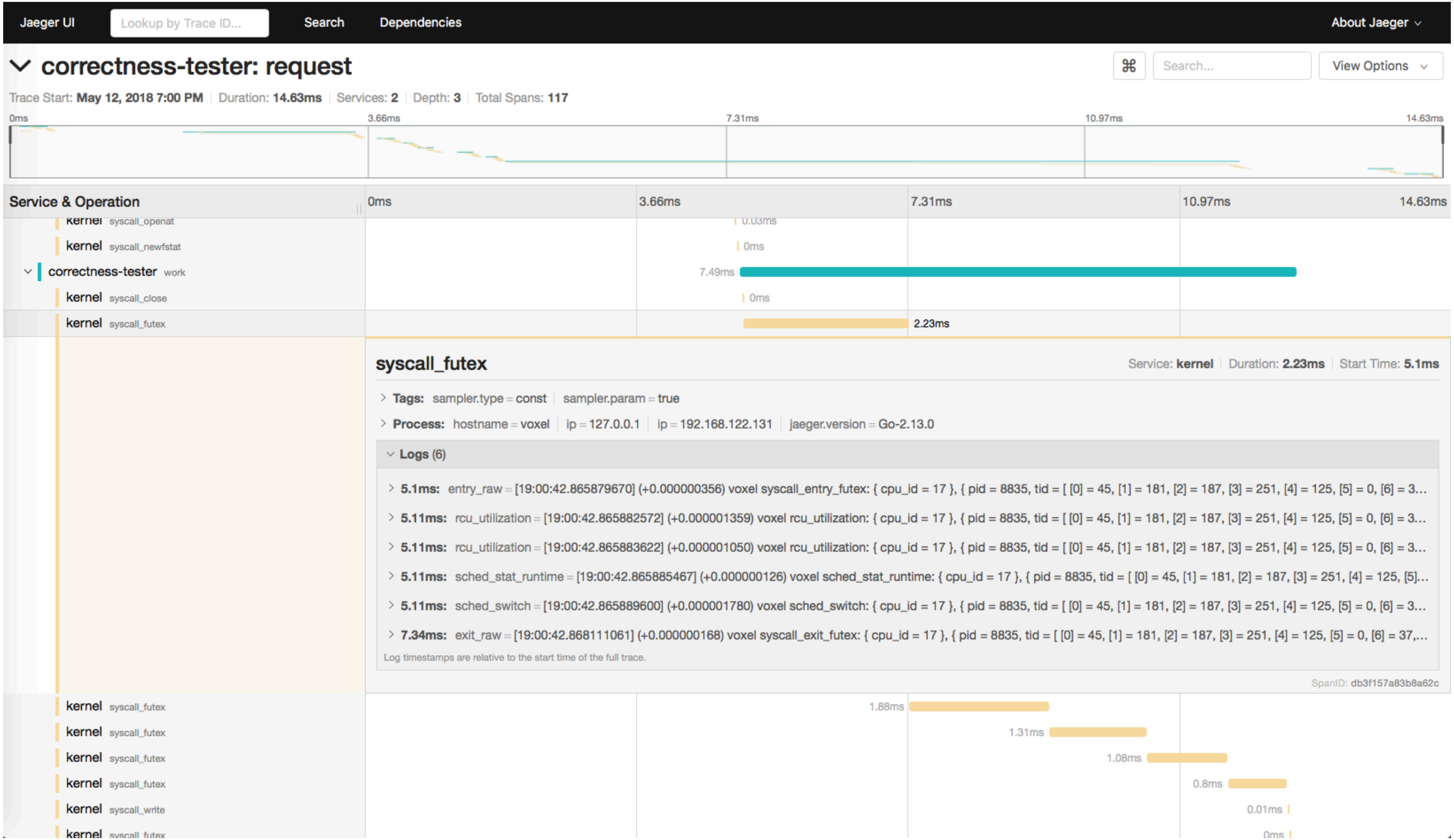
- Raja Sambasivan - Mentor

- MIT PRIMES

Backup Slides

Syscalls made by correctness tester

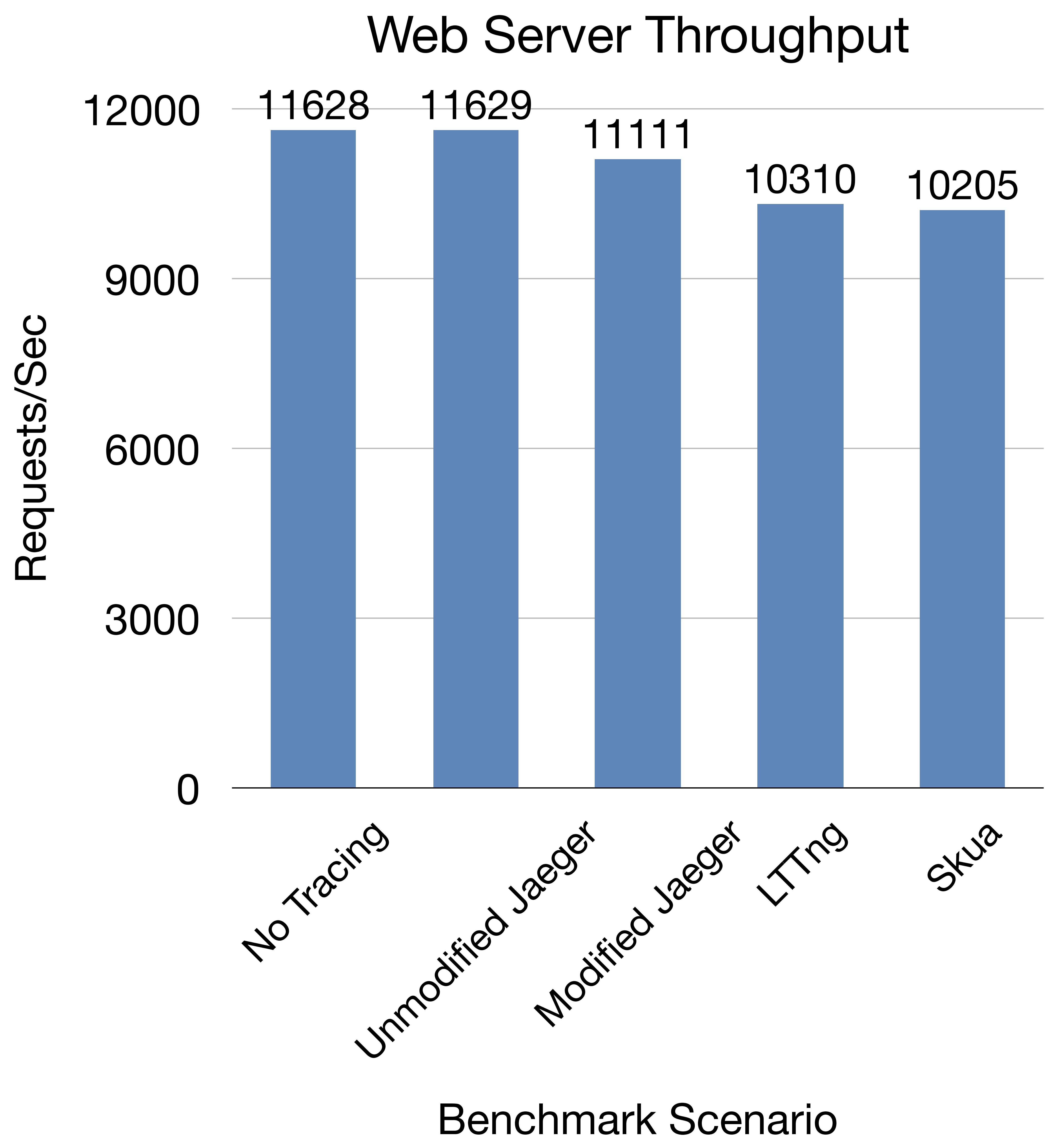
- `getpid`
- `getppid`
- `gettid`
- `gettimeofday`
- `nanosleep`
- `open`
- `close`
- `write`
- `fstat`
- `futex`

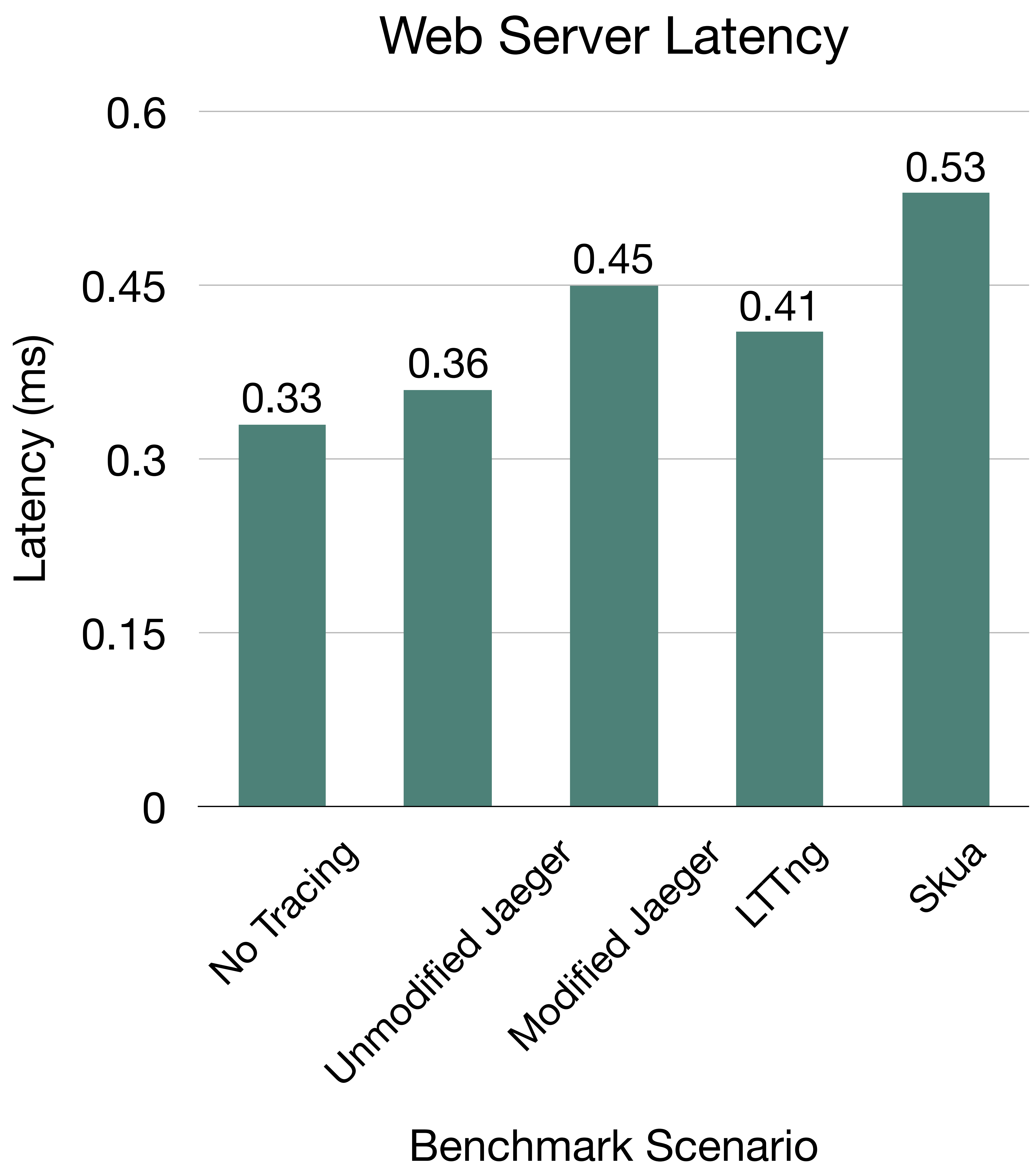

Jaeger UI
Lookup by Trace ID...
Search
Dependencies
About Jaeger
correctness-tester: request
Search...
View Options
Trace Start: May 12, 2018 7:00 PM | Duration: 14.63ms | Services: 2 | Depth: 3 | Total Spans: 117
0ms
3.66ms
7.31ms
10.97ms
14.63ms
Service & Operation
kernel syscall_openat
0.03ms
kernel syscall_newfstat
0ms
correctness-tester work
7.49ms
kernel syscall_close
0ms
kernel syscall_futex
2.23ms
syscall_futex
Service: kernel | Duration: 2.23ms | Start Time: 5.1ms
Tags: sampler.type = const | sampler.param = true
Process: hostname = voxel | ip = 127.0.0.1 | ip = 192.168.122.131 | jaeger.version = Go-2.13.0
Logs (6)
5.1ms: entry_raw = [19:00:42.865879670] (+0.000000356) voxel syscall_entry_futex: { cpu_id = 17 }, { pid = 8835, tid = [[0] = 45, [1] = 181, [2] = 187, [3] = 251, [4] = 125, [5] = 0, [6] = 3...
5.11ms: rcu_utilization = [19:00:42.865882572] (+0.000001359) voxel rcu_utilization: { cpu_id = 17 }, { pid = 8835, tid = [[0] = 45, [1] = 181, [2] = 187, [3] = 251, [4] = 125, [5] = 0, [6] = 3...
5.11ms: rcu_utilization = [19:00:42.865883622] (+0.000001050) voxel rcu_utilization: { cpu_id = 17 }, { pid = 8835, tid = [[0] = 45, [1] = 181, [2] = 187, [3] = 251, [4] = 125, [5] = 0, [6] = 3...
5.11ms: sched_stat_runtime = [19:00:42.865885467] (+0.000000126) voxel sched_stat_runtime: { cpu_id = 17 }, { pid = 8835, tid = [[0] = 45, [1] = 181, [2] = 187, [3] = 251, [4] = 125, [5]...
5.11ms: sched_switch = [19:00:42.865889600] (+0.000001780) voxel sched_switch: { cpu_id = 17 }, { pid = 8835, tid = [[0] = 45, [1] = 181, [2] = 187, [3] = 251, [4] = 125, [5] = 0, [6] = 3...
7.34ms: exit_raw = [19:00:42.868111061] (+0.000000168) voxel syscall_exit_futex: { cpu_id = 17 }, { pid = 8835, tid = [[0] = 45, [1] = 181, [2] = 187, [3] = 251, [4] = 125, [5] = 0, [6] = 37,...
Log timestamps are relative to the start time of the full trace.
SpanID: db3f157a83b8a62c
kernel syscall_futex
1.88ms
kernel syscall_futex
1.31ms
kernel syscall_futex
1.08ms
kernel syscall_futex
0.8ms
kernel syscall_write
0.01ms
kernel syscall_futex
0ms

Performance Benchmark Details

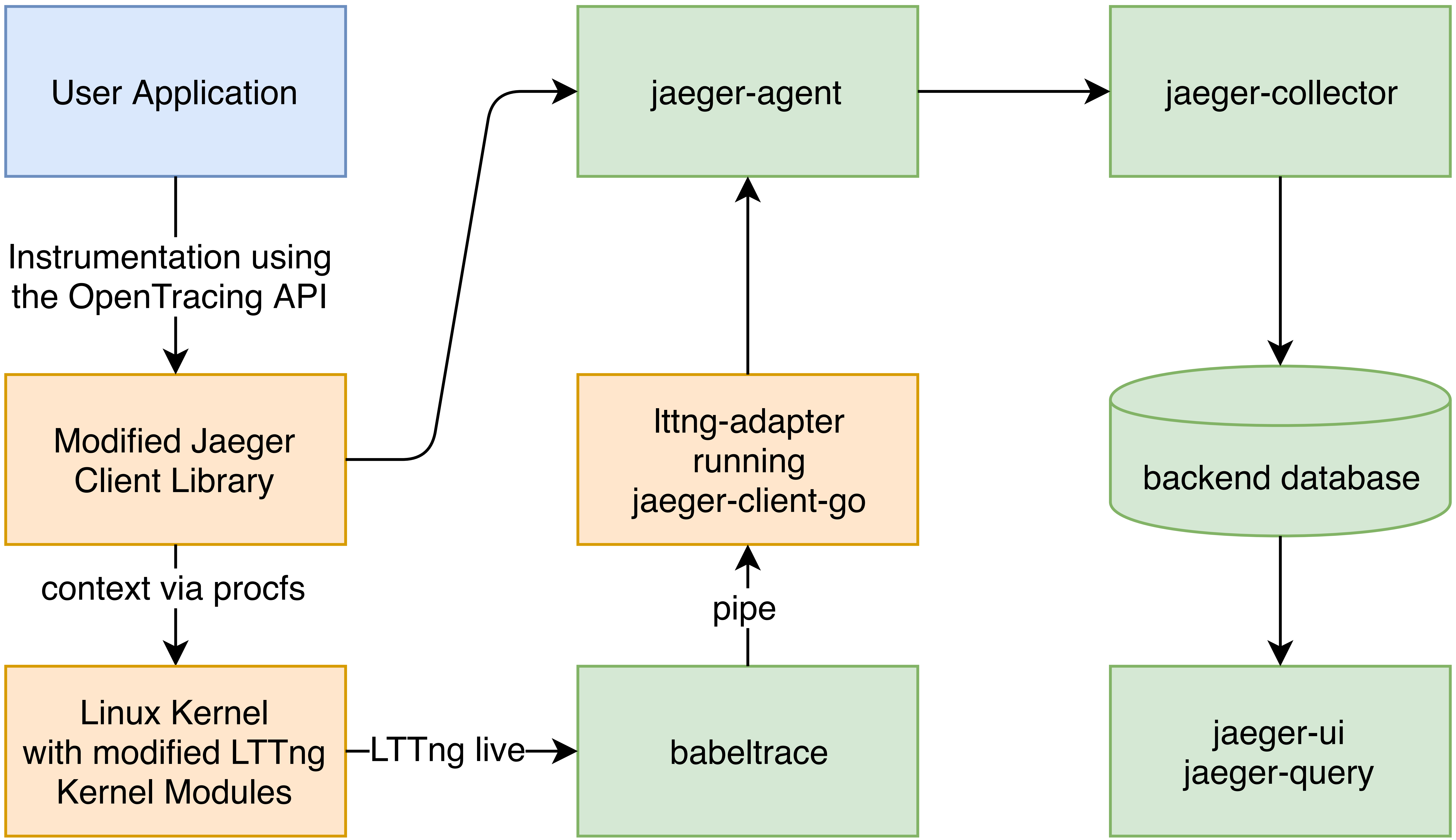
- Tests run on KVM virtual machine assigned 24 vCPUs (2 × Intel Xeon X5670), 16 GB RAM, with latest Arch Linux updates

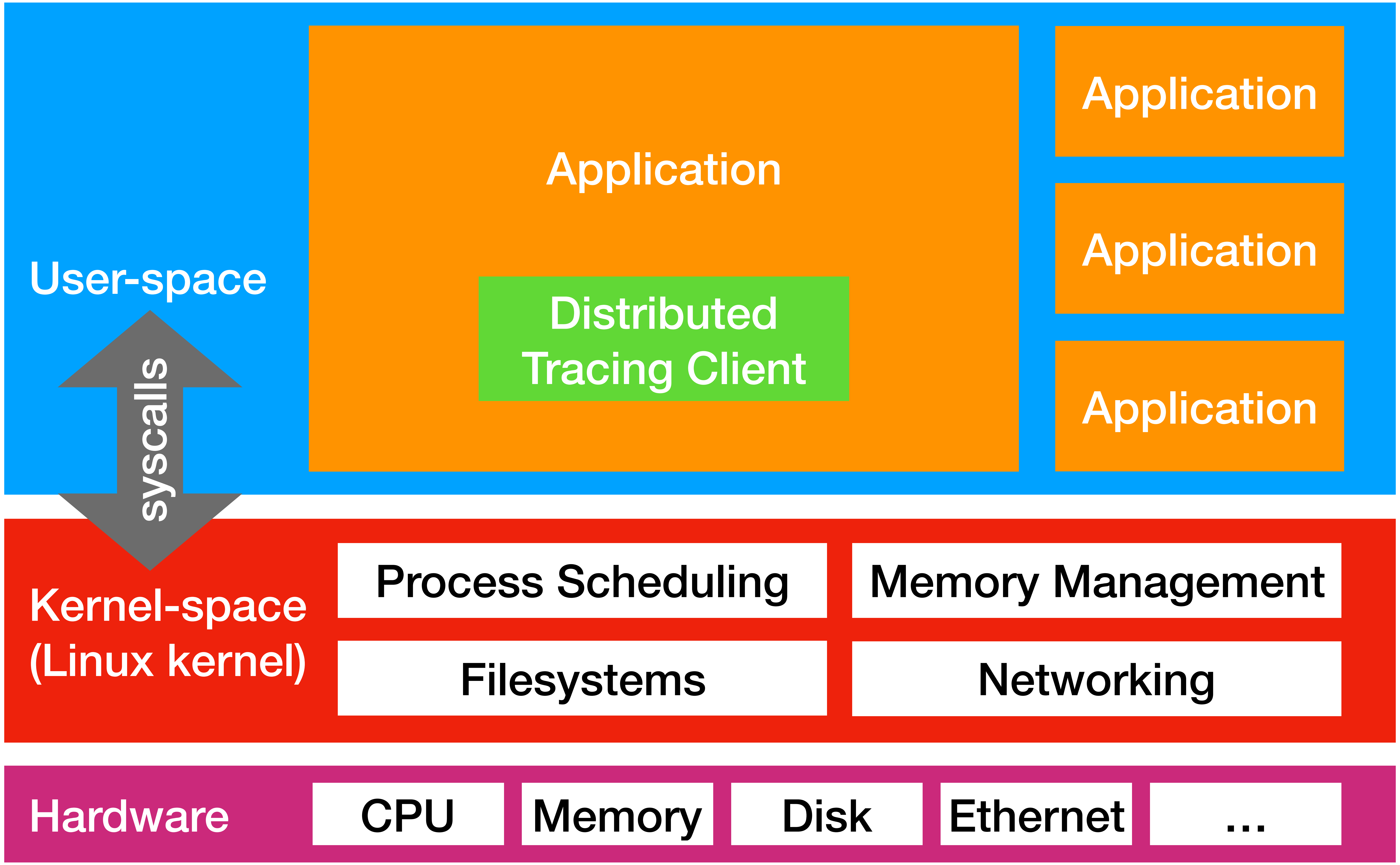
Benchmark Scenario	Program Instrumentation	Kernel Tracing via LTTng
No Tracing	N/A	No
Unmodified Jaeger	Original Jaeger Client	No
Modified Jaeger	Modified Jaeger Client	No
LTTng	N/A	Yes, but output ignored
Skua	Modified Jaeger Client	Yes, output sent to adapter


Web Server Throughput
Requests/Sec
12000
9000
6000
3000
0
11628
11629
11111
10310
10205
No Tracing
Unmodified Jaeger
Modified Jaeger
LTTng
Skua
Benchmark Scenario


Web Server Latency
Latency (ms)
0.6
0.45
0.3
0.15
0
0.33
0.36
0.45
0.41
0.53
No Tracing
Unmodified Jaeger
Modified Jaeger
LTTng
Skua
Benchmark Scenario

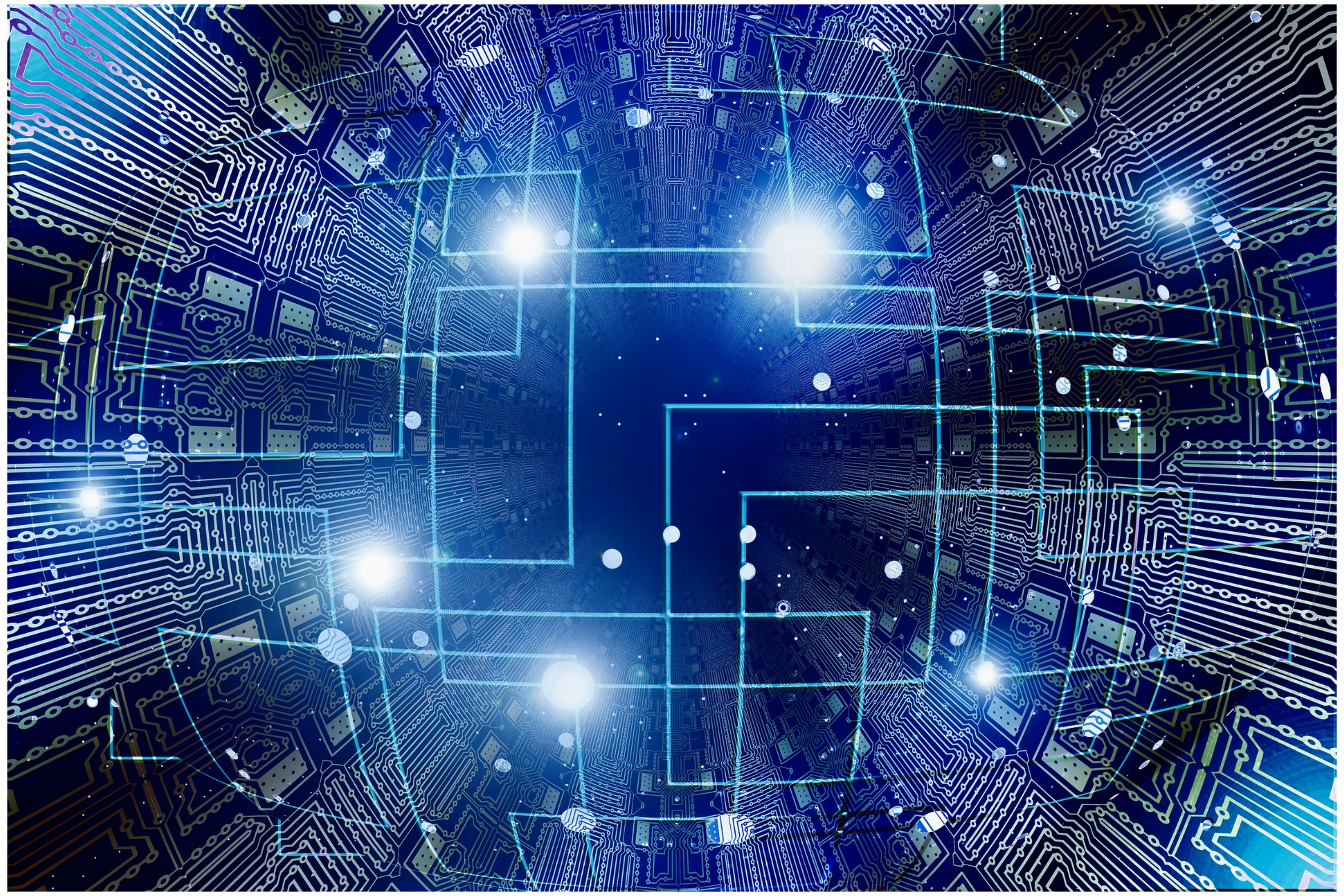
Skua Implementation Details



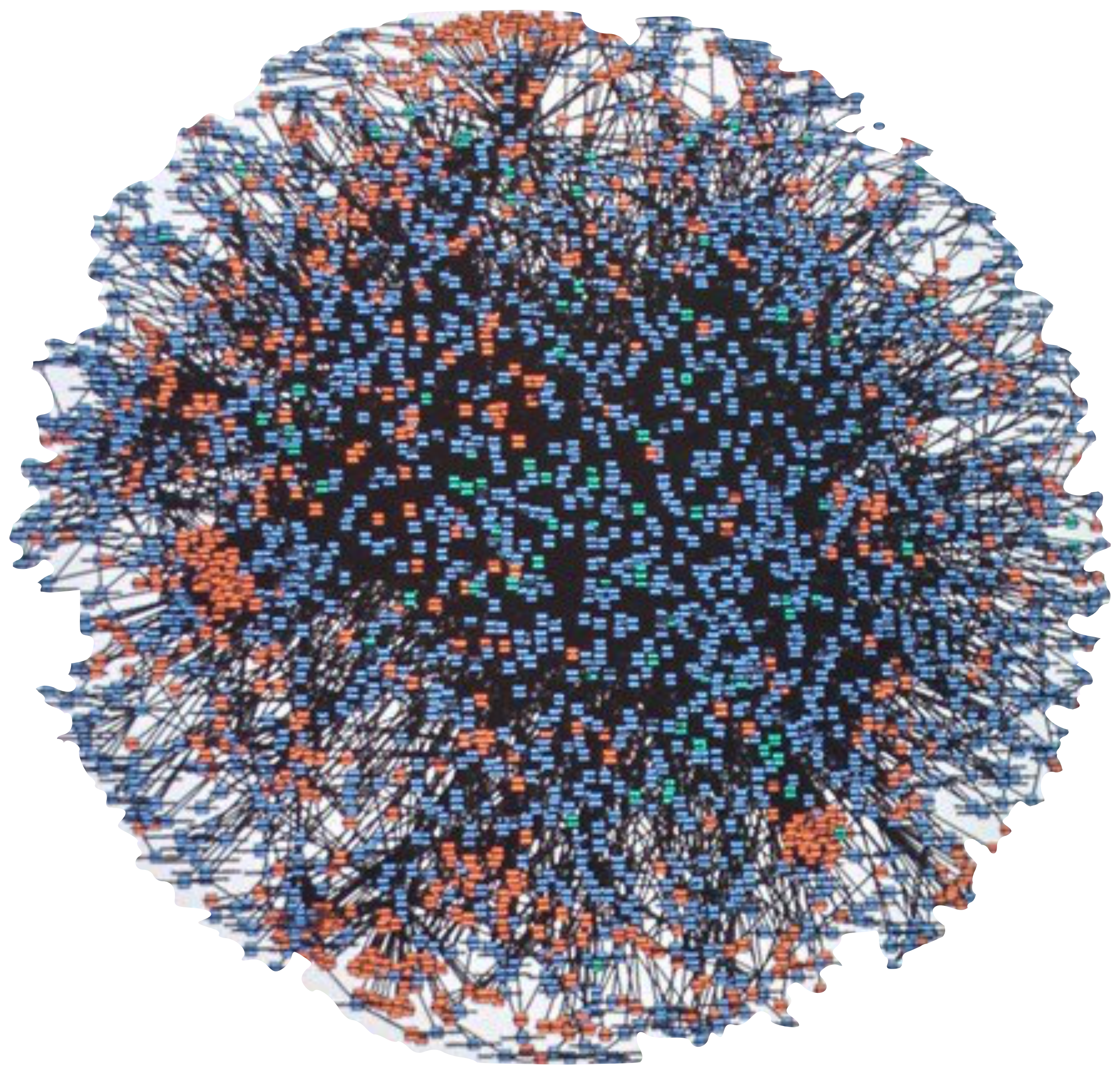

Application
Application
Application
Application
Distributed Tracing Client
User-space
syscalls
Kernel-space (Linux kernel)
Process Scheduling
Memory Management
Filesystems
Networking
Hardware
CPU
Memory
Disk
Ethernet
…

Existing Tracing Frameworks

- Dapper (2010) — Google
- Zipkin (2012) —Twitter
- Canopy (2017) — Facebook
- Jaeger (2017) — open sourced by Uber

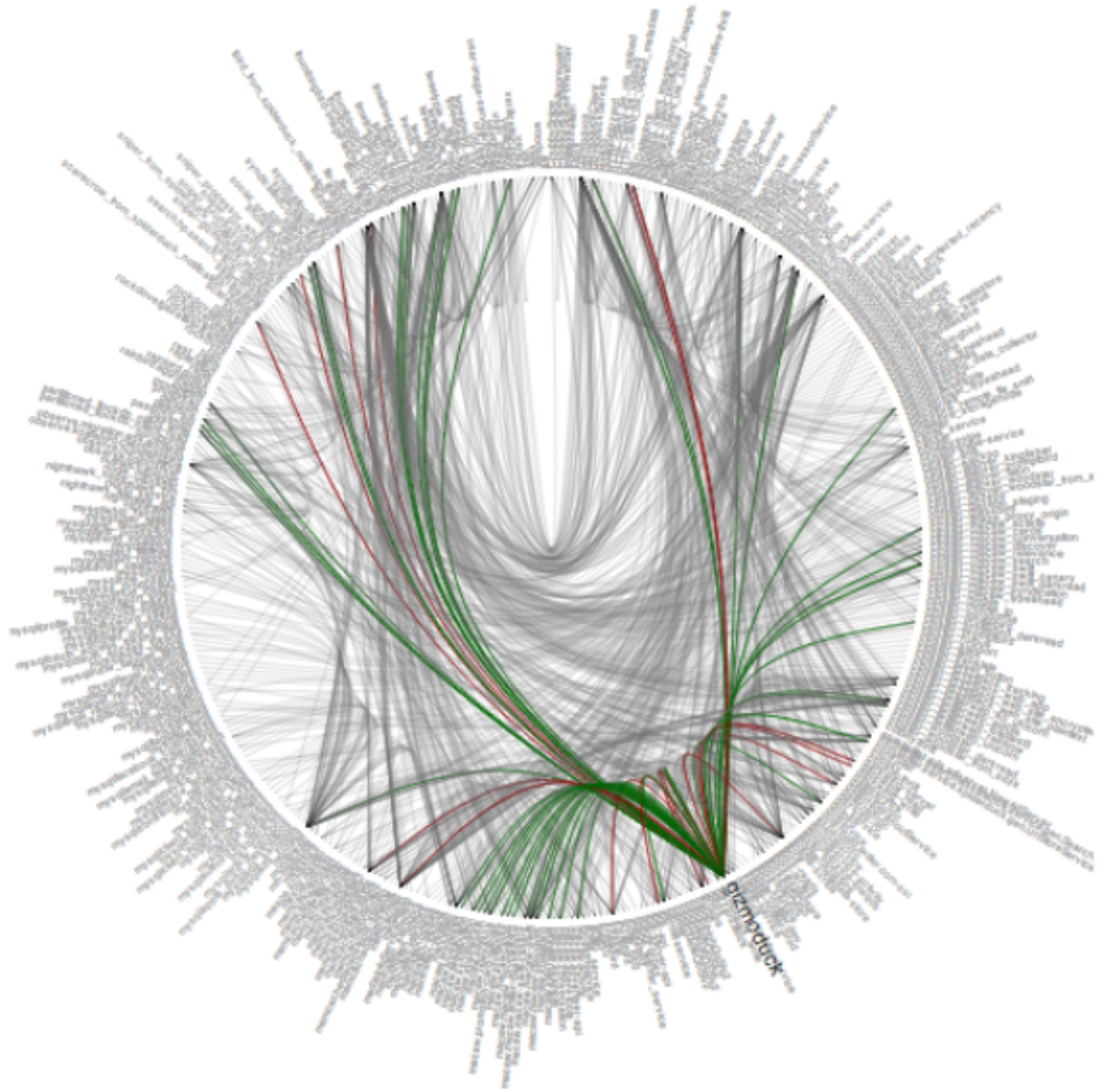


Distributed Systems



AWS (2008)

Netflix (2012)



Twitter (2013)

AWS: https://twitter.com/werner/status/741673514567143424
Netflix: https://www.slideshare.net/BruceWong3/the-case-for-chaos
Twitter: https://blog.twitter.com/engineering/en_us/a/2013/observability-at-twitter.html