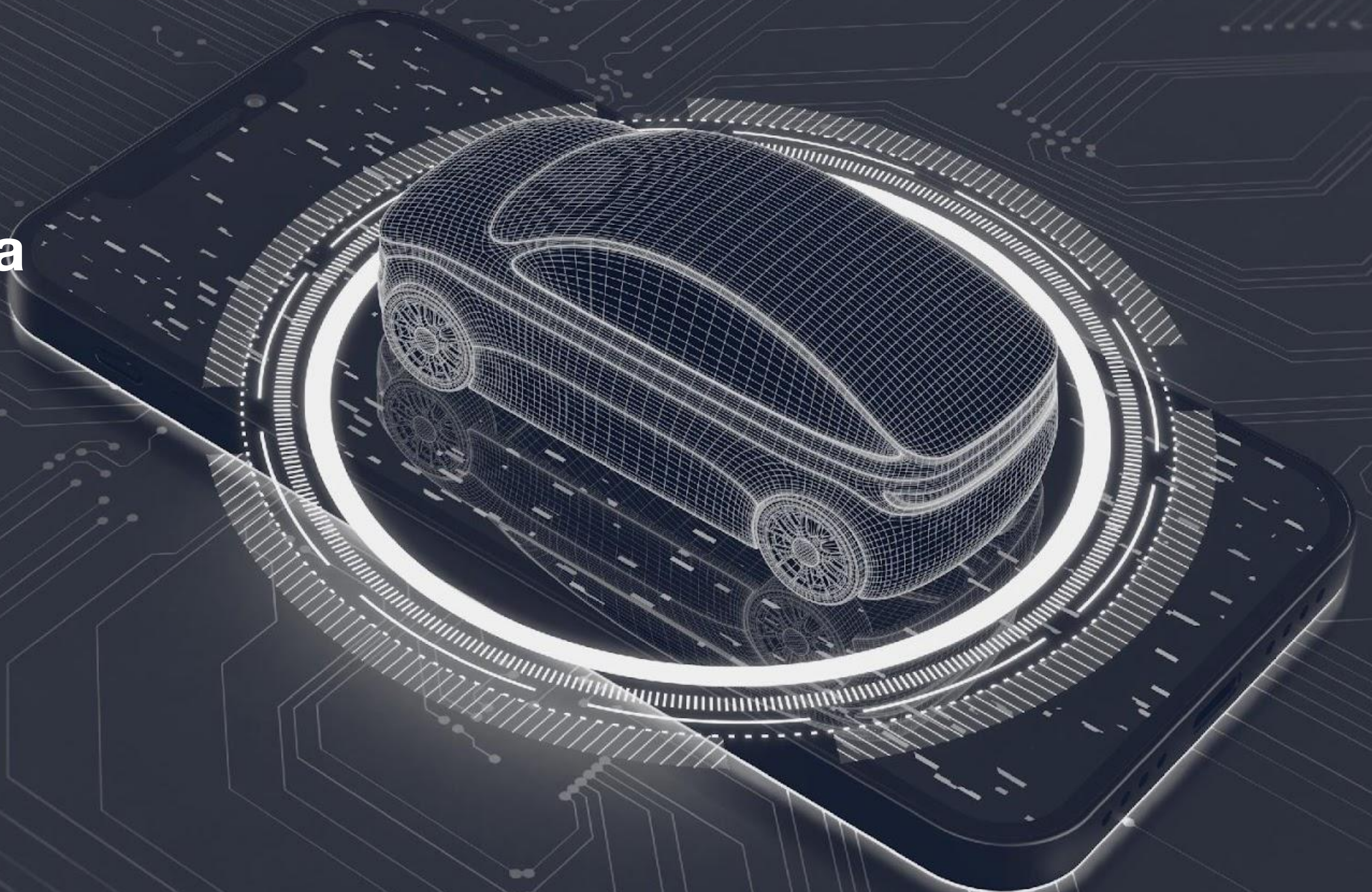
ROSCon 2023

Apex.AI

Improving your application's algorithms and optimizing performance using trace data



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October 20, 2023

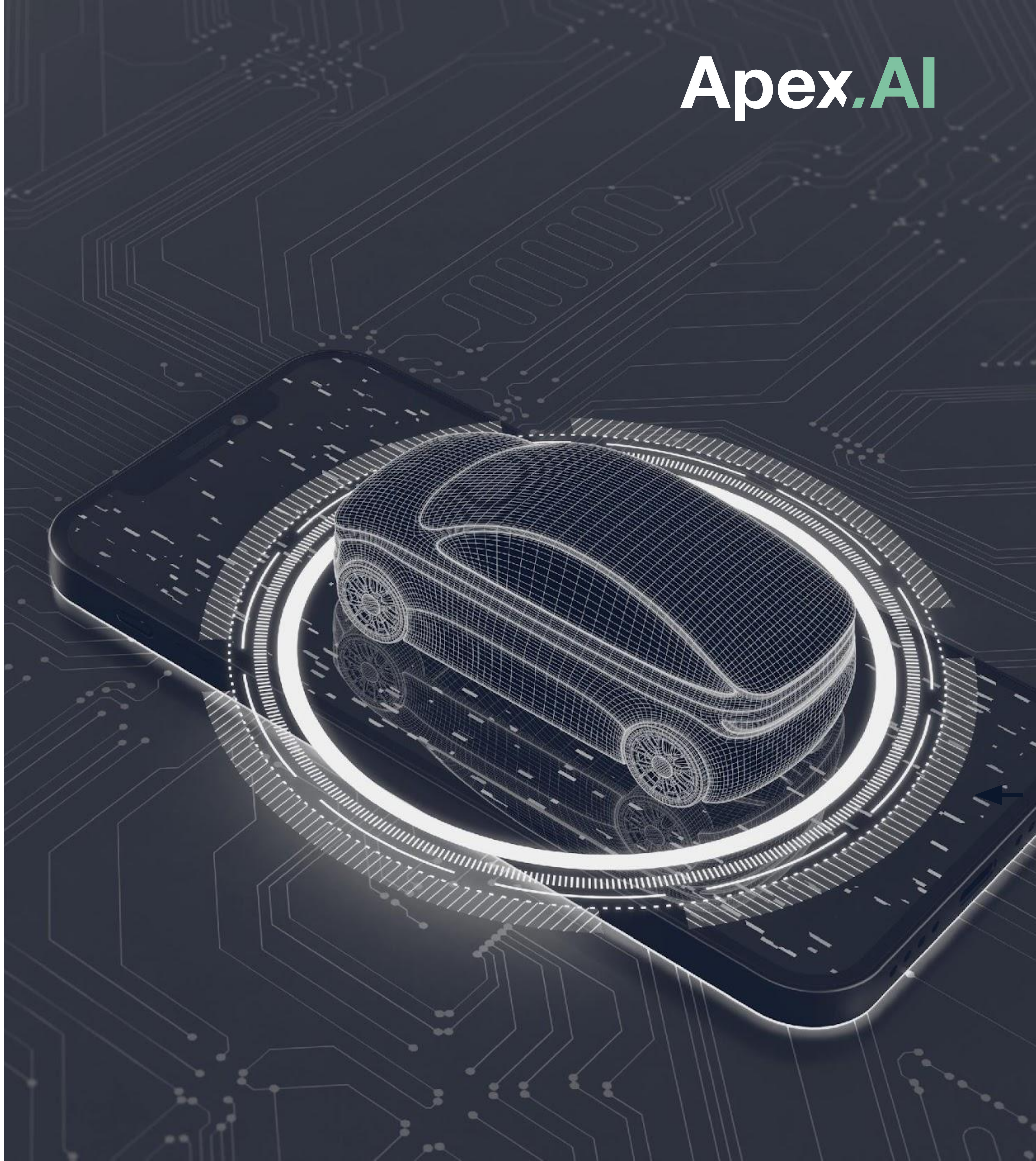
Agenda

We'll learn how to use trace data to improve performance

1. Introduction
2. Tracing
3. Instrumentation
4. Trace data analysis
5. Examples and use-cases
6. Conclusion

Introduction

- Performance analysis
- Understand what happened during execution
- Extract high-level information
- Find cause of bugs
- Identify misconfigurations
- Optimize performance
- Extract various performance metrics



Tracing

- Low-level software tracing
  - Fast low-level recording at runtime
  - Low performance impact
  - Payload is usually raw binary data
  - Needs to be processed for it to be useful
- Need to instrument source code in order to collect data
  - Applications
  - Linux kernel (built-in)
  - Drivers
  - Etc.
- `ros2_tracing`: tracing instrumentation and tools for ROS 2
- This presentation is about trace data processing, not `ros2_tracing` itself
  - See ROS World 2021 presentation: *Tracing ROS 2 with ros2_tracing* (vimeo.com/652633418)
  - Or the paper: *ros2_tracing: Multipurpose Low-Overhead Framework for Real-Time Tracing of ROS 2* (doi.org/10.1109/LRA.2022.3174346)

- Record low-level execution information
- Trace data needs to be processed

Why trace? When to trace?

- Tracing is one of many tools in our huge toolbox
- Not always the right tool
  - Optimize a specific function or lines of code ➡️ profiler
  - Debug a specific function or lines of code ➡️ debugger
  - What happened at 9:27 pm? ➡️ logs
- Tracing examples
  - One instance is taking longer than usual: I/O, kernel scheduling, etc.
  - Anomalies or unexpected behaviour with messages or system: logic bug, executor misconfiguration, etc.
- Especially useful to understand complex systems
  - Like large and/or distributed systems
  - Since complex systems can make debuggers less effective
- Also useful in general to visualize a system
  - Might give hints to optimize your system
  - Even if you’re not necessarily looking for performance issues

Tracing is useful to understand the execution of complex systems.

Instrumentation — `ros2_tracing`

- Instrumentation is built into ROS 2 by default on Linux starting from ROS 2 Iron Irwini
- Information about the main elements of ROS 2
- Objects
  - Node, publisher, subscription, timer
- Events
  - Callback execution (subscription, timer)
  - Message publication, message taking
  - Internal executor phases, etc.
- Uses the LTTng tracer for instrumentation and recording

- Information about callbacks and messages
- Now included by default on Linux as of ROS 2 Iron Irwini

Instrumentation — Custom

1. Define your tracepoints in a tracepoint provider (shared library)
   a. Tracepoint names
   b. Arguments
2. Add tracepoints to your code
3. Run your application and collect data

```
$  ros2 trace --ust 'ros2:*' 'my_app:*'
```

- This is a simplified version
- For more information, see: lttng.org/docs/v2.13/#doc-instrumenting

```c
// tp.h: tracepoint definition in tp provider header
#include <lttng/tracepoint.h>
LTTNG_UST_TRACEPOINT_EVENT(
  my_app, my_tracepoint,
  LTTNG_UST_TP_ARGS(int, count_arg),
  LTTNG_UST_TP_FIELDS(
    lttng_ust_field_integer(int, count, count_arg))
)


// Insert tracepoint somewhere in your code
#include "tp.h"
lttng_ust_tracepoint(my_app, my_tracepoint, 42);
```

Trace data analysis — How to use trace data?

- Combining trace data from multiple sources helps understand the execution
  - Multiple applications, including ROS 2 + additional application-specific info
  - Linux kernel
  - Distributed systems (with time synchronization)
- Examples
  - ROS 2: callback executions, message publications
  - Linux kernel: scheduling, I/O, system calls, etc.
- Add information specific to your own nodes
  - Instrument and trace your nodes
  - Can provide information about the processing performed by your nodes
- Trace processing tools
  - `tracetools_analysis`: very basic Python API
  - Eclipse Trace Compass: powerful trace viewer and analysis framework
- Trace Compass can display Linux kernel and ROS 2 trace data
  - And more!

Combine and visualize trace data from multiple sources or layers.

Example

- Viewing ROS 2 trace data with Trace Compass
- Horizontal axis is time
- Rows
    - 🤖 system (1 trace/system)
        - 🔲 node
            - ⌛ timer
            - ↘️ subscription
            - ↗️ publisher
- Shows
    - Rectangles: callback executions
    - Arrows: message publications

- Autoware reference_system
- For a single end-to-end process pipeline instance starting from one LiDAR message

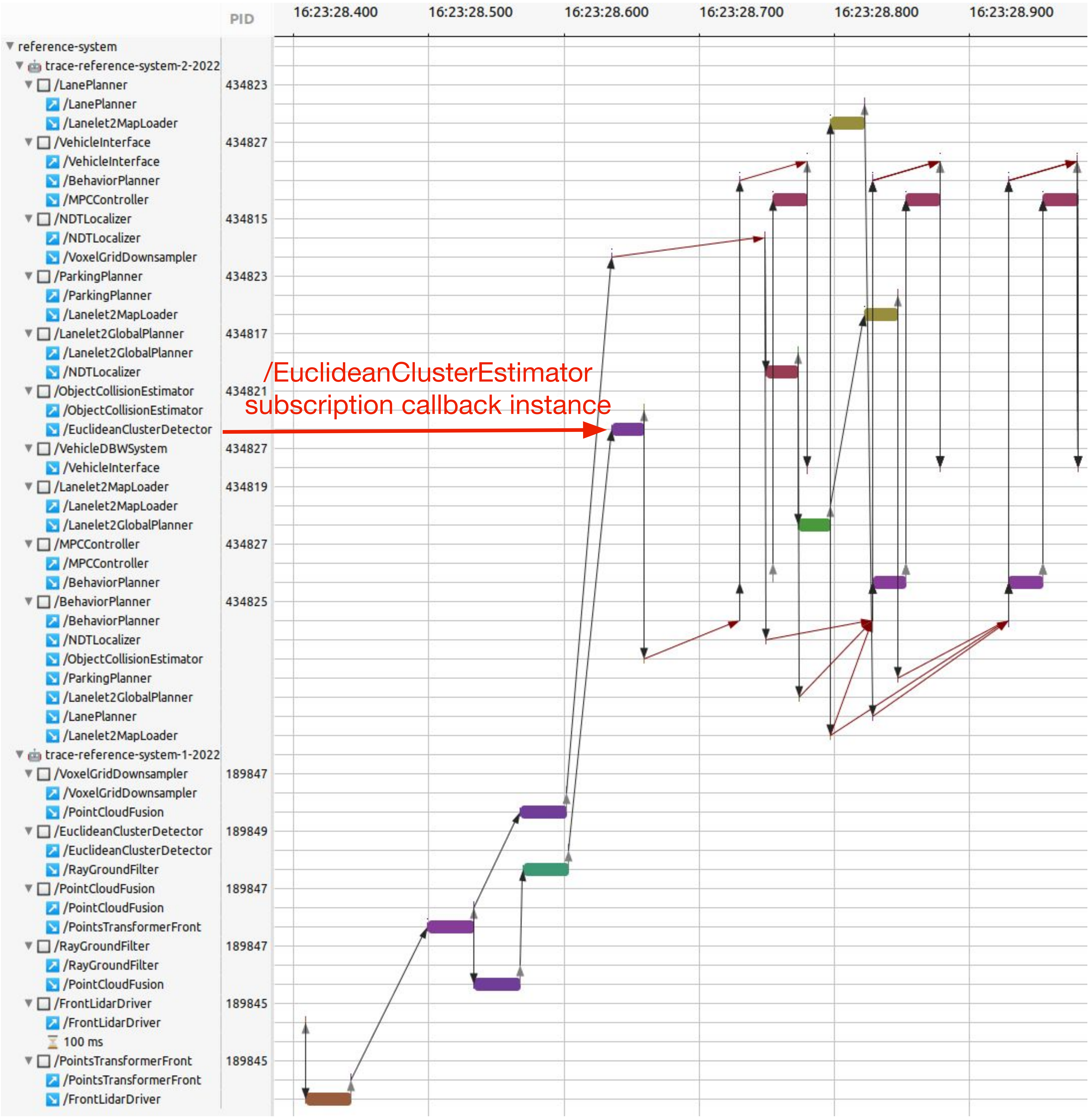
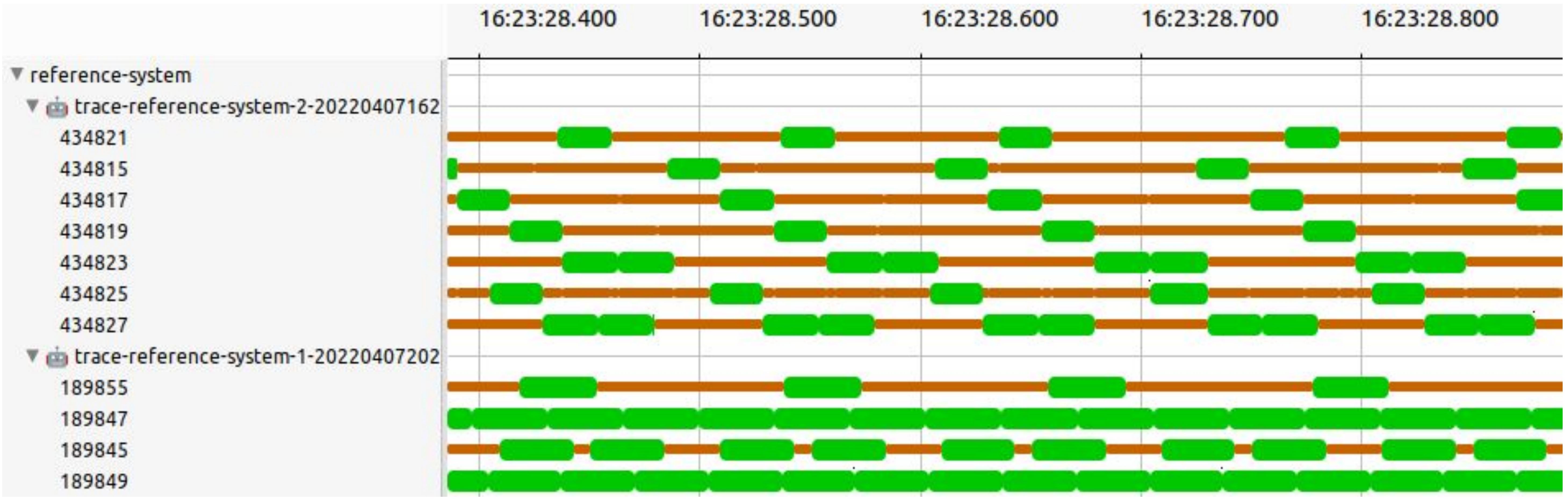


Figure 1. Callbacks and messages over time in Trace Compass.

Example (2)

- State of executors over time
  - Green: executing (callback)
  - Orange: waiting for work
- 1 executor/process
- Some executors are busier than others
- Could explain message processing delays
  - Message reception → callback



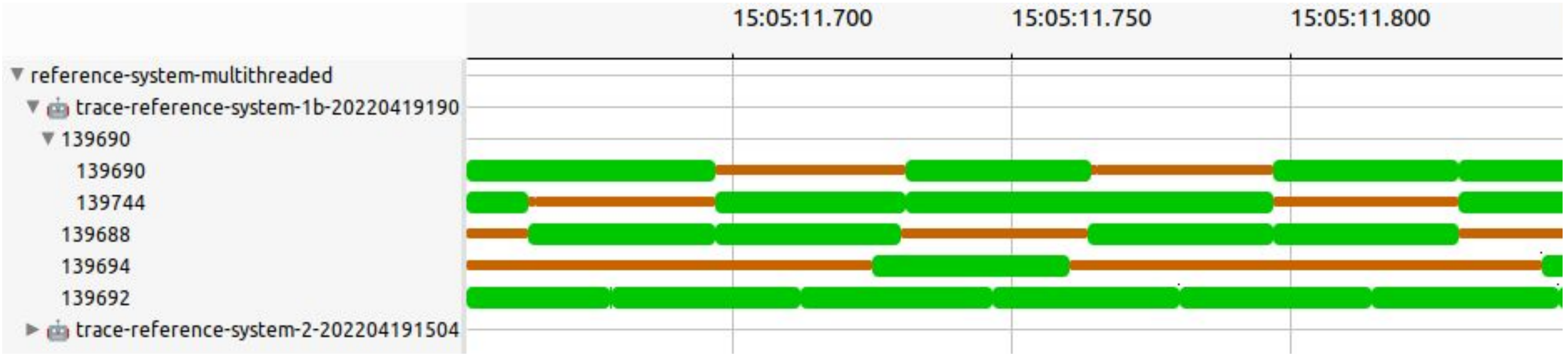


Figure 2. State of single-threaded executors over time.
Figure 3. State of multi-threaded and single-threaded executors over time.

Example (3)

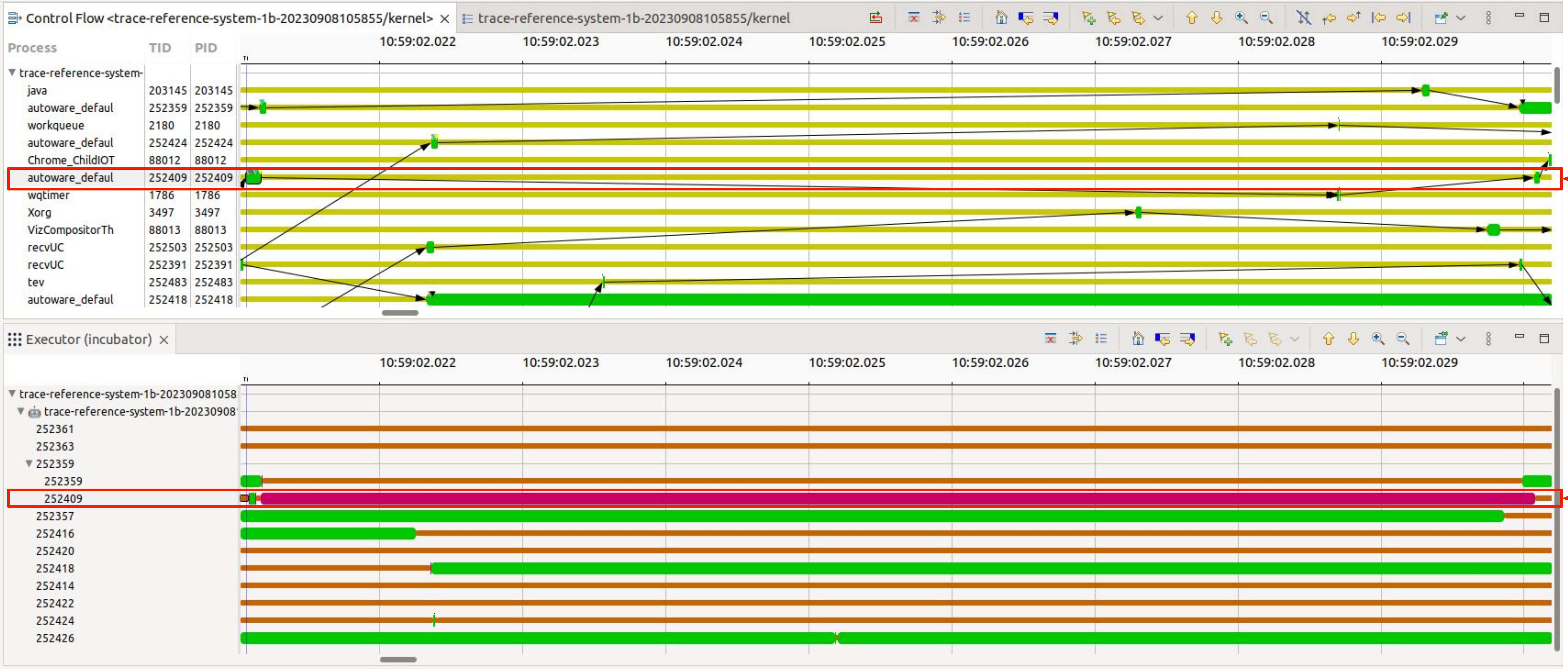


Figure 4. Kernel scheduling view (control flow) vs. executor view: thread scheduling explains some executor delays.

Example — Taking it to the next level

- We've implemented a Trace Compass plugin for Apex.Grace, our fork of ROS 2
- This is somewhat specific to our custom executor
    - Executor-centric view (below) vs. node-centric (previously)
    - See presentation from ROS World 2021 executor workshop: *Executor with wait-set and polling subscription*

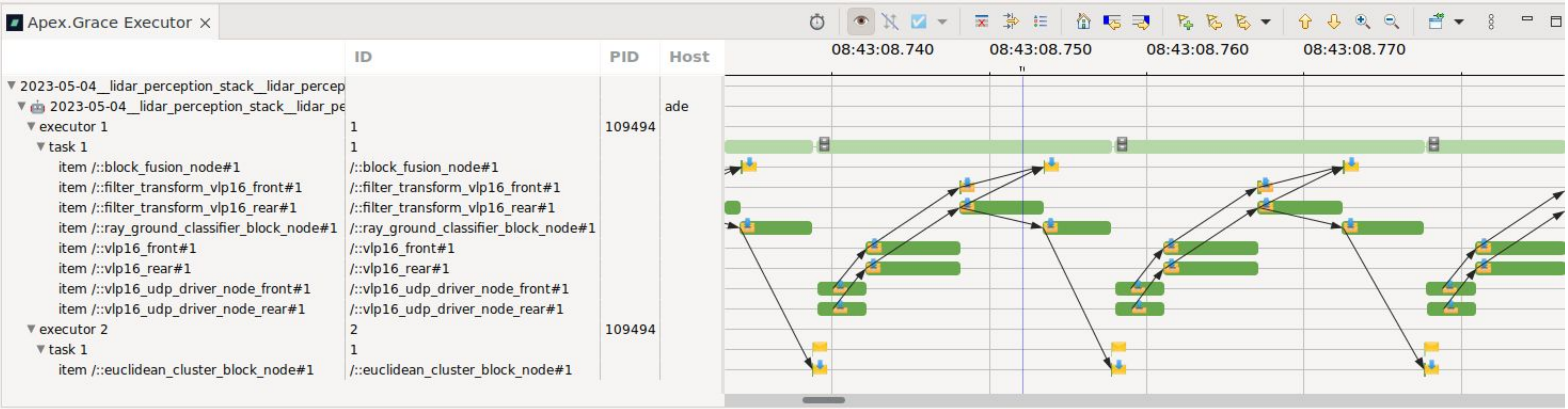


Figure 5. State of Apex.Grace executor and message publications over time.

Example — Taking it to the next level (2)

- We can see the callback executions over time
  - What if we want to know more about what happens in our callback?
- Custom tracepoints to provide information about processing done inside a function or callback
- Display durations over time

```
lttng_ust_tracepoint(interval_start, "camera msg", (uint64_t) id);
// Do some processing
// ...
lttng_ust_tracepoint(interval_end, "camera msg", (uint64_t) id);
```

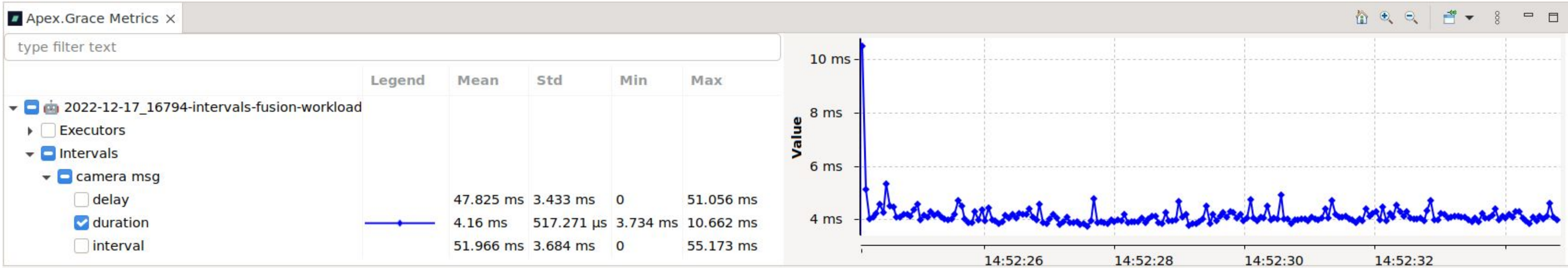


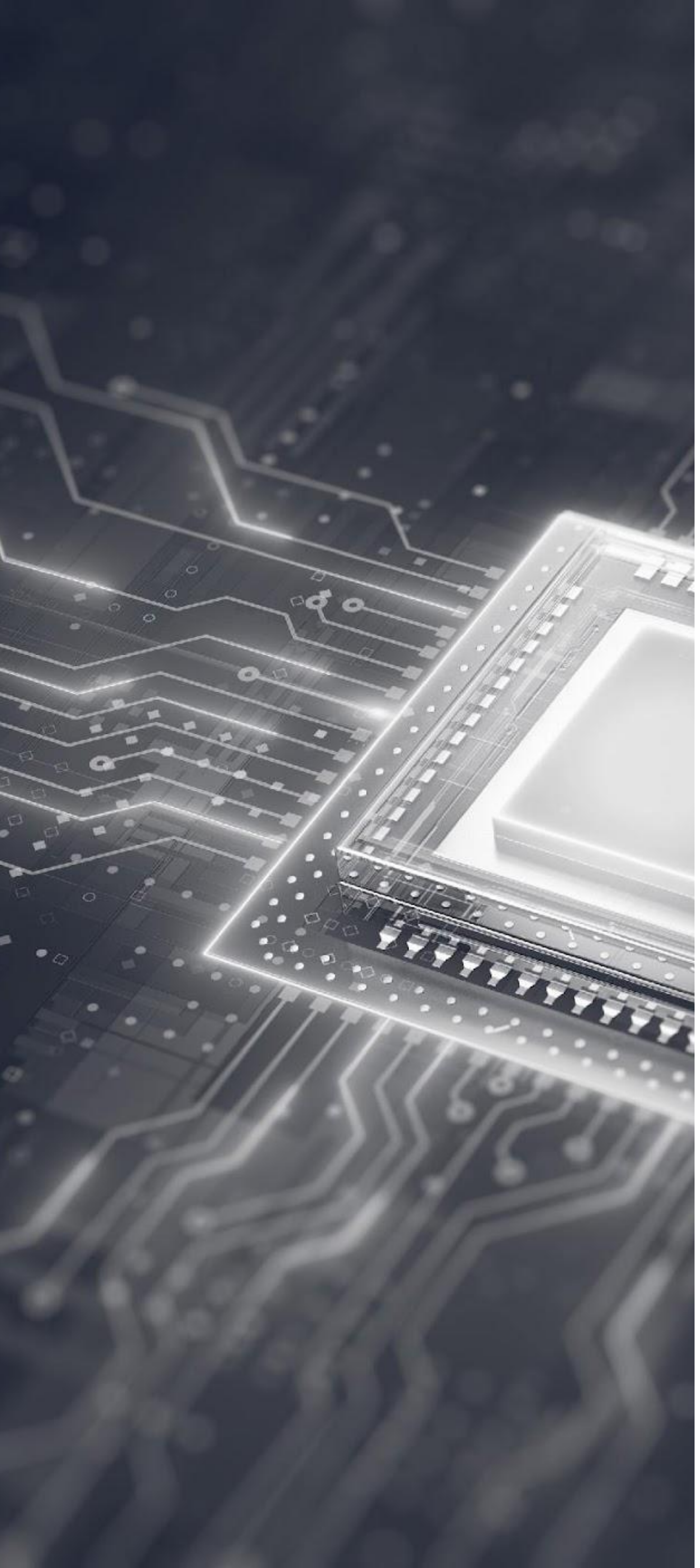
Figure 6. Duration (interval_end - interval_start) values over time.

Use-cases — Our own experience

- Using tracing and our Trace Compass-based tool, we've identified and fixed multiple issues

- Executor misconfiguration
  - Very visually obvious, but would've never guessed otherwise
  - I wasn't even looking for an issue
- Performance issue
  - Could clearly see that a node couldn't process messages fast enough: bottleneck
- Performance instability due to bad execution logic
  - Would've been hard to find otherwise
- Execution strategy optimization for our LiDAR stack
  - Compare different execution strategies both visually and using KPIs
  - Make changes and optimize
  - Useful for system integrators, not only for core application developers

Being able to visualize the execution of your system is very powerful, even if you're not really looking for issues.



Conclusion

- Tracing can help understand the execution of an application
  - Even if you’re not looking for performance issues!
- Collect trace data from multiple sources and analyze the combined data
- ROS 2 has built-in tracing instrumentation
- Eclipse Trace Compass can display ROS 2 trace data
  - Could use a bit more love, though!
- Add custom application-specific instrumentation
- Implement your own Trace Compass plugin

Thank you!

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Links

- github.com/ros2/ros2_tracing
- tracecompass.org
- github.com/christophebedard/ros2-message-flow-analysis
- github.com/christophebedard

Relevant papers

- C. Bédard, I. Lütkebohle, and M. Dagenais, "**ros2_tracing: Multipurpose Low-Overhead Framework for Real-Time Tracing of ROS 2,**" *IEEE Robotics and Automation Letters*, vol. 7, no. 3, pp. 6511–6518, 2022.
- C. Bédard, P.-Y. Lajoie, G. Beltrame, and M. Dagenais, "**Message Flow Analysis with Complex Causal Links for Distributed ROS 2 Systems,**" *Robotics and Autonomous Systems*, vol. 161, p. 104361, 2023.