Doctoral Program in Informatics (PDINF)

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Flexible Tracing and Analysis of Applications' I/O Behavior

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Data-centric and Distributed Systems

- Critical services increasingly rely on efficient data access and processing
- Complex architectures
  - Large codebases
    - Fluent Bit: ≈1M LoC, 5K files, 4 languages
    - TensorFlow: >4M LoC, 20K files, 3K contributors
  - Several components
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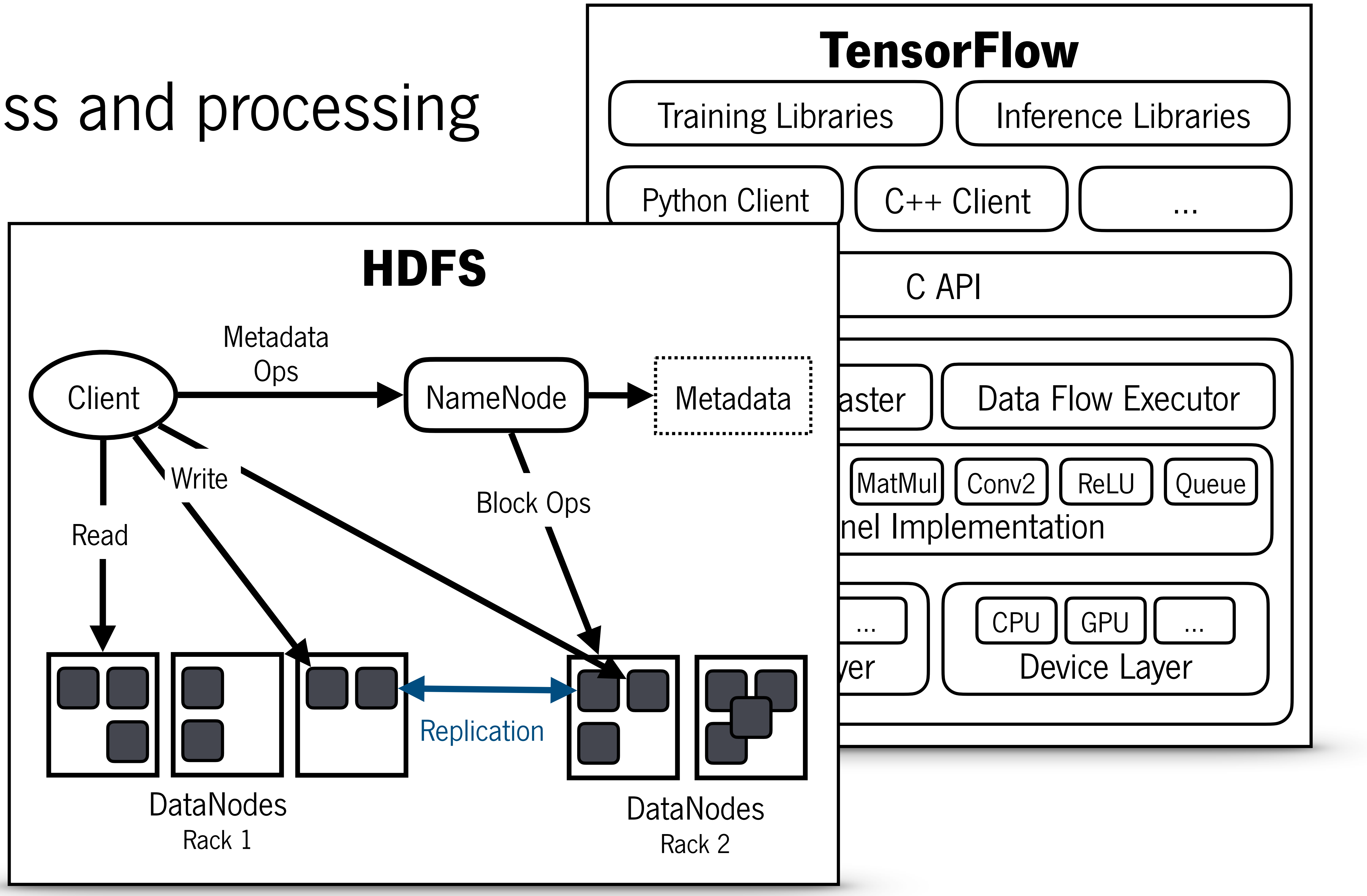

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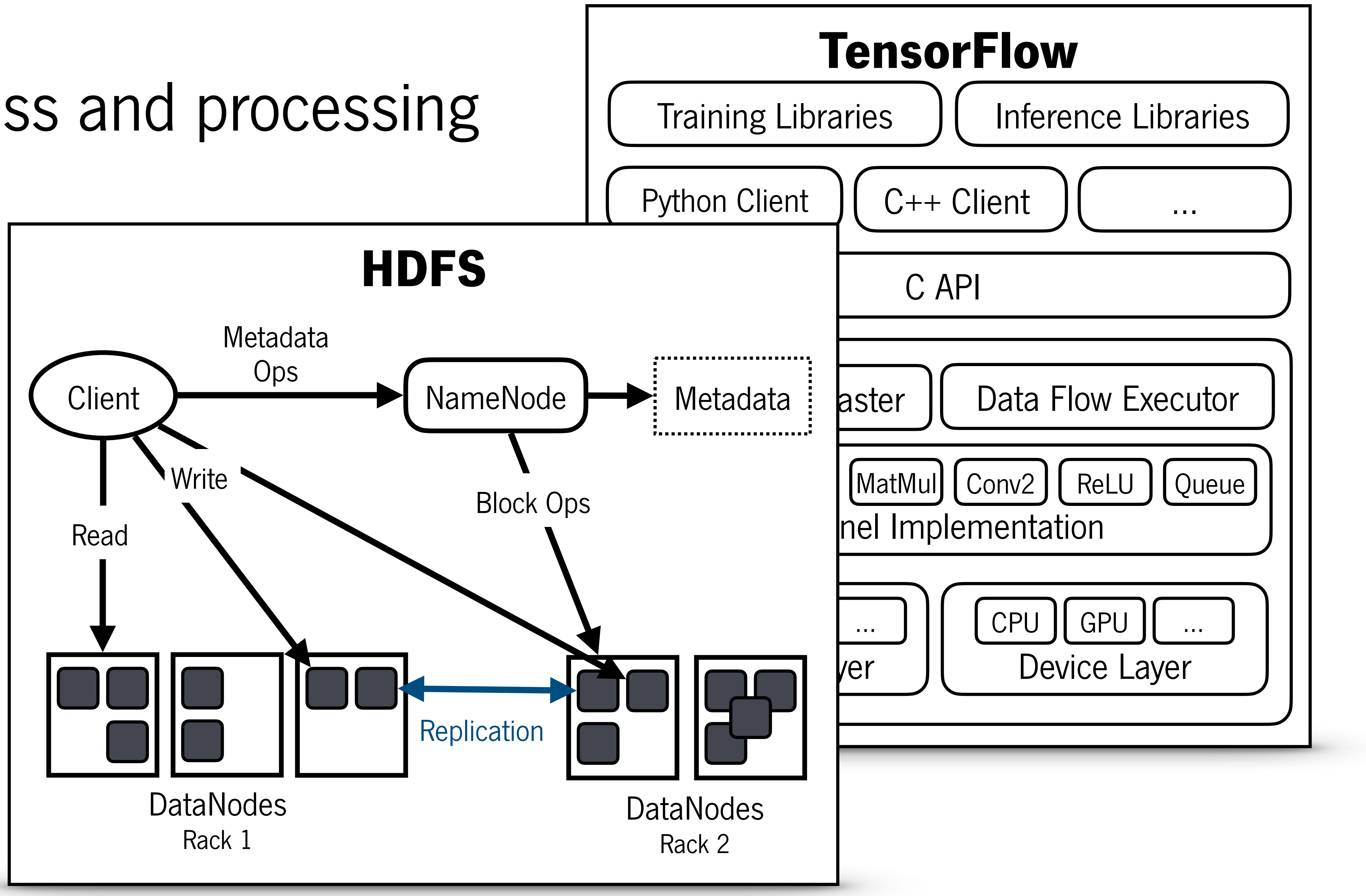
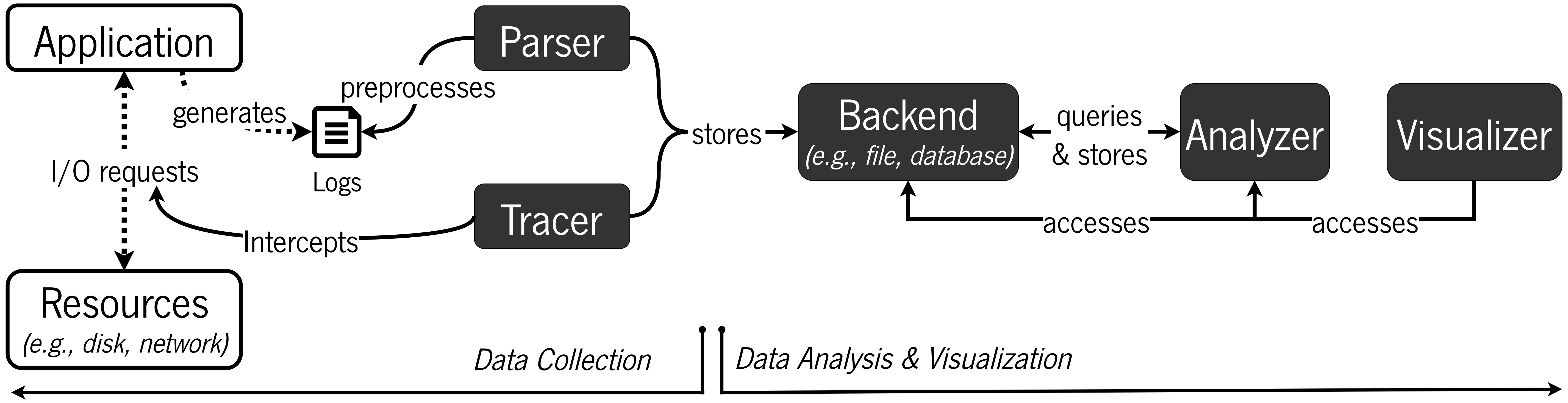


Question: How can we ensure the correctness and good performance of these systems?

Diagnosis Pipelines

- Provide the collection, analysis and visualization of I/O requests made by applications
- Useful for:
  - Debugging - uncover the root cause of errors, inefficiencies and unattained performance
  - Validation - validate applications' expected behaviors and the corrections of errors
  - Exploration - understand how applications and storage systems handle data requests



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◉ #4 - Scope

- Design comprehensive solutions for diagnosing different kinds of I/O behaviors

Contributions

◉ **Content-aware Diagnosis with CaT**

- Enables the collection and analysis of distributed systems' I/O requests

◉ **Comprehensive and Flexible Diagnosis with DIO**

- Provides customizable and insightful diagnosis of data-centric applications' storage I/O

◉ **Custom and Improved Analysis with CRIBA**

- Offers specialized and automated analysis of cryptographic ransomware I/O behavior

Content-Aware Diagnosis

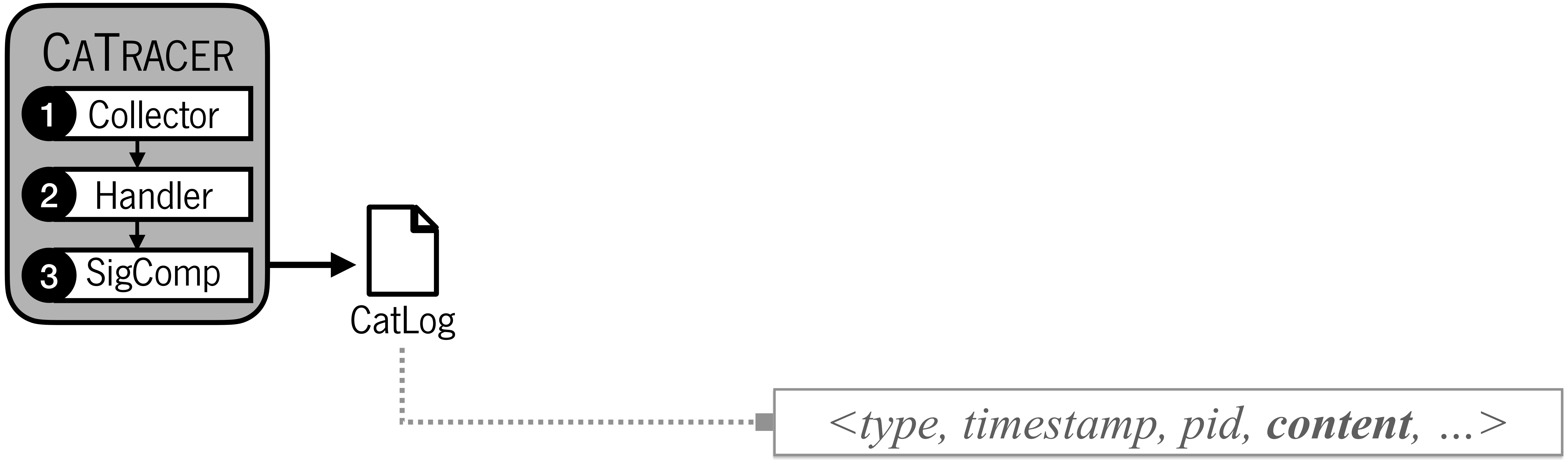
CAT, a framework for diagnosing I/O flow of distributed systems

- Collects requests' context and content
- Combines causality inference with data similarity techniques
- Pinpoints data flow throughout the components of distributed systems

CaT Design

▢ Falcon’s original component ⬚ Falcon’s modified component ▨ New components

CaT Design



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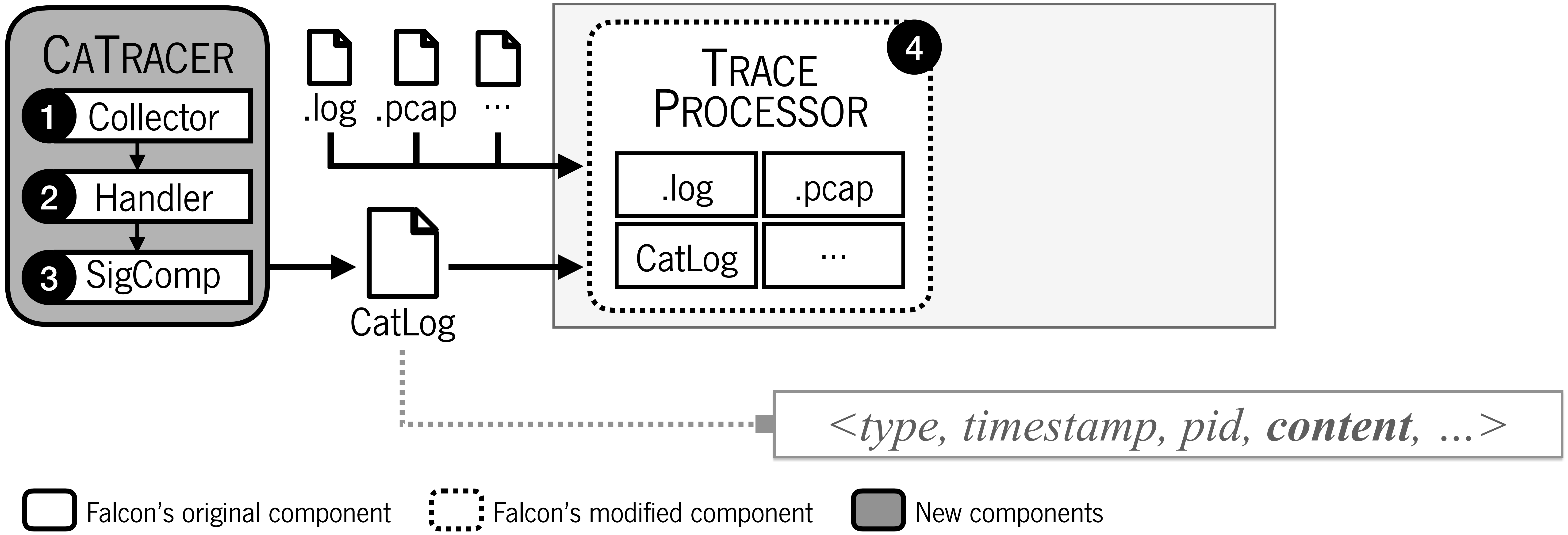

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- **Trace Processor**: Parses and organizes events into different data structures

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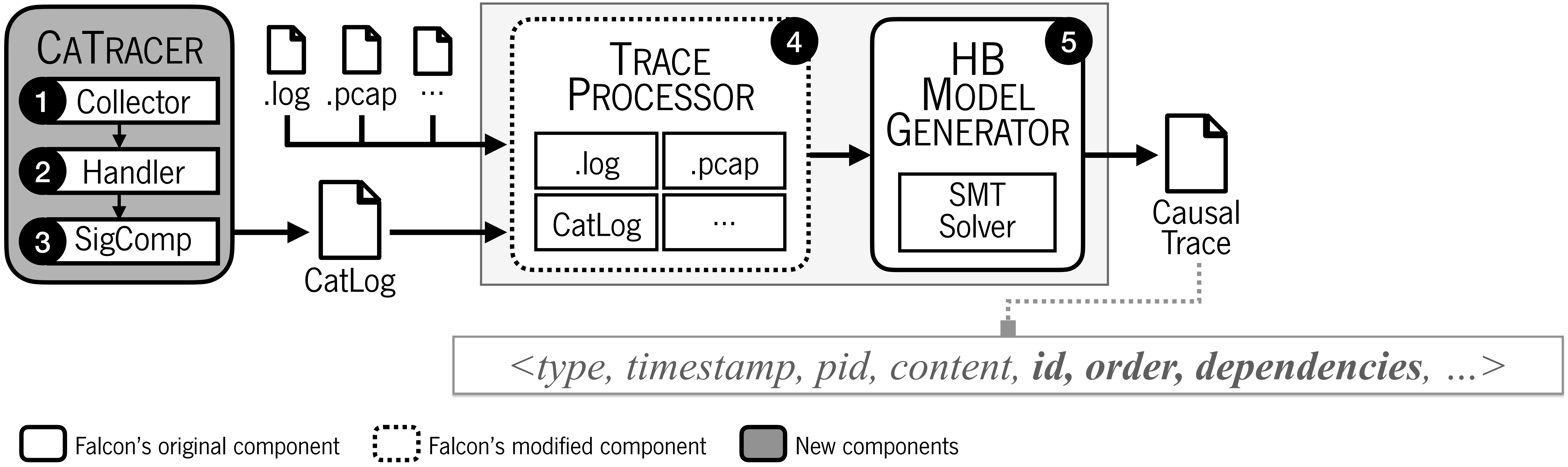

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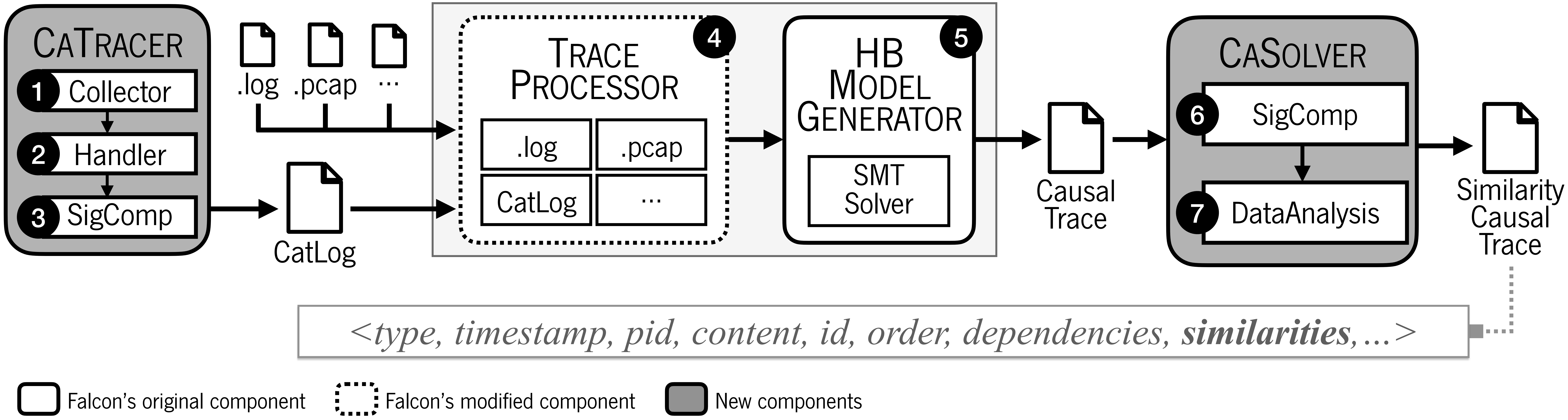

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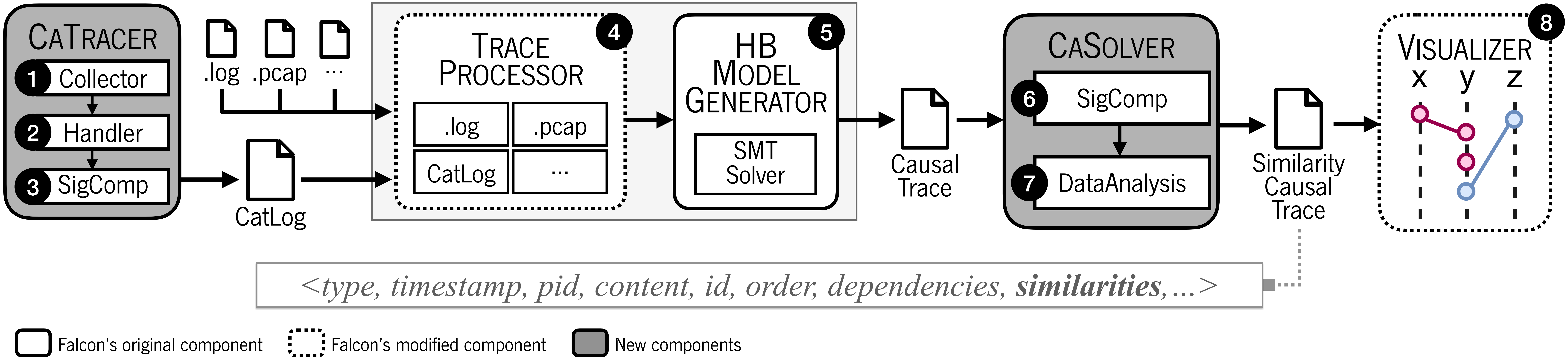

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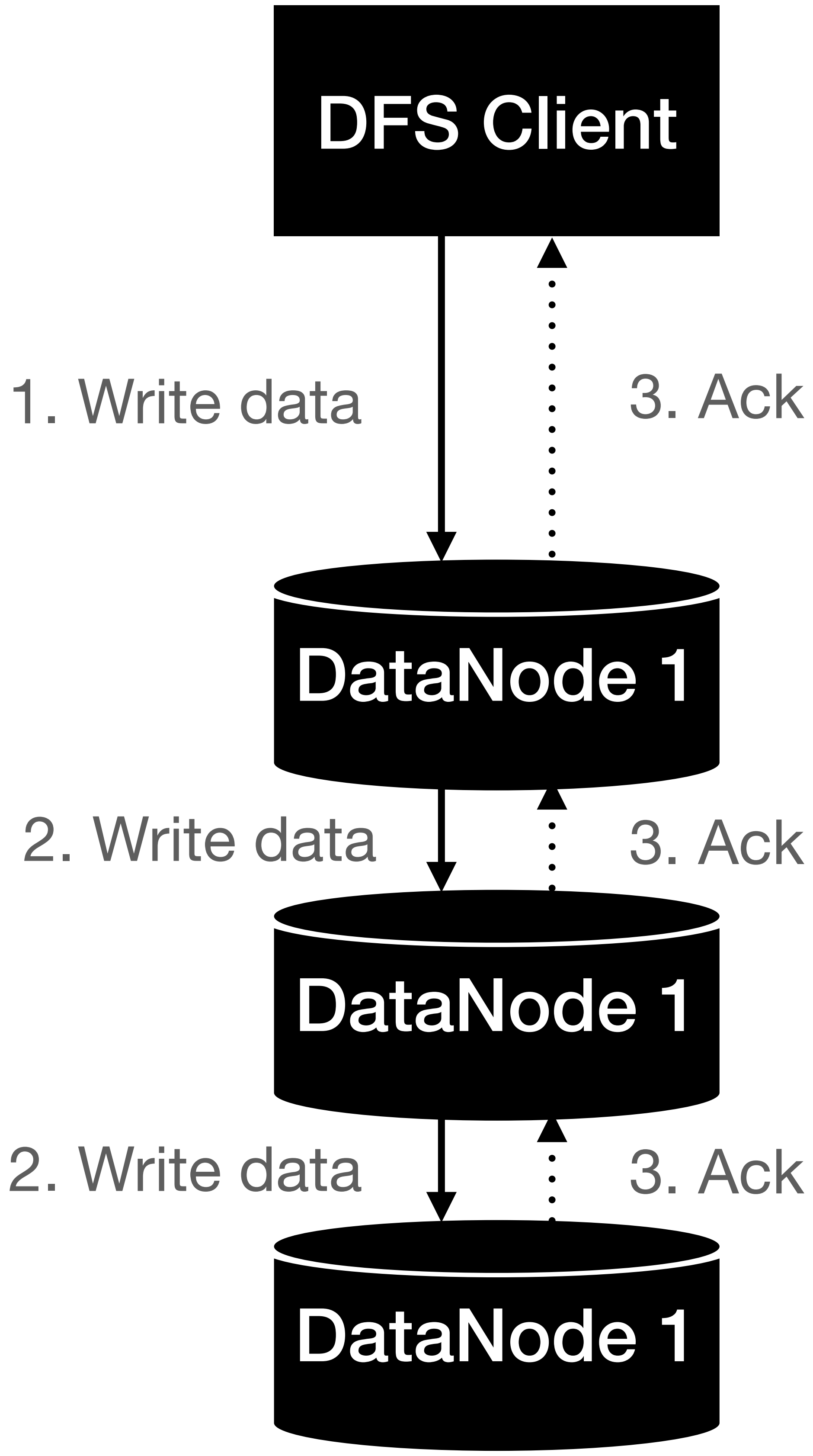
- **Visualizer**: Builds space-time diagrams representing the execution, the events' causal relationship and their data flow

CaT in Action

Storage and Replication of a file in HDFS

- **HDFS:** Hadoop distributed file system composed of several DataNodes
- **Replication Process:**
  - Clients send file(s) to one DataNode
  - DataNodes forward data to other nodes and then persist it on disk
  - The process is repeated until all DataNodes have the clients' data
- **3 Test Scenarios:**
  - <u>Normal execution</u>
  - <u>Storage corruption</u>: data modified before being persisted
  - <u>Network corruption</u>: data modified before being transmitted



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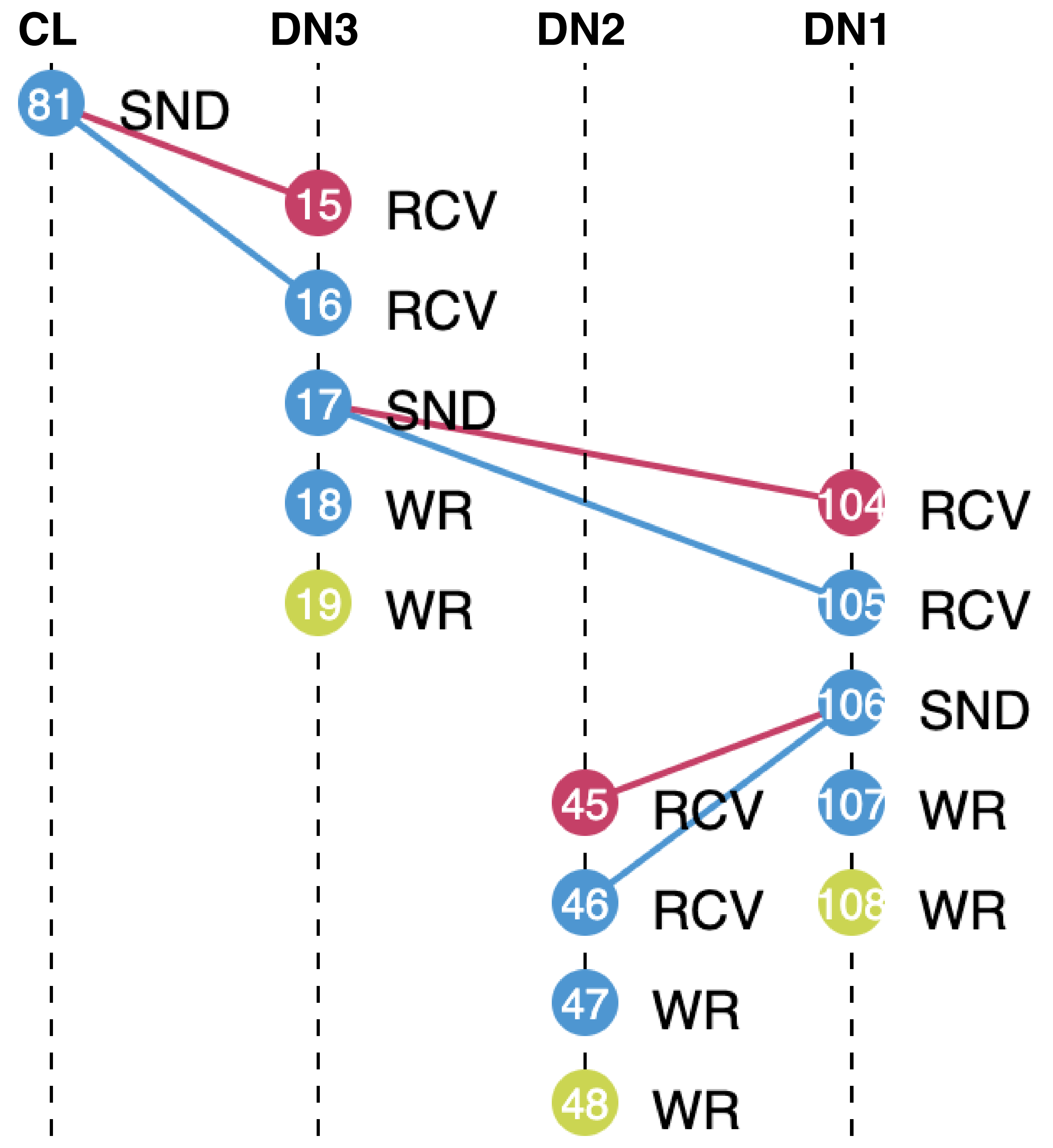

a) Normal execution

All DataNodes persist client's data

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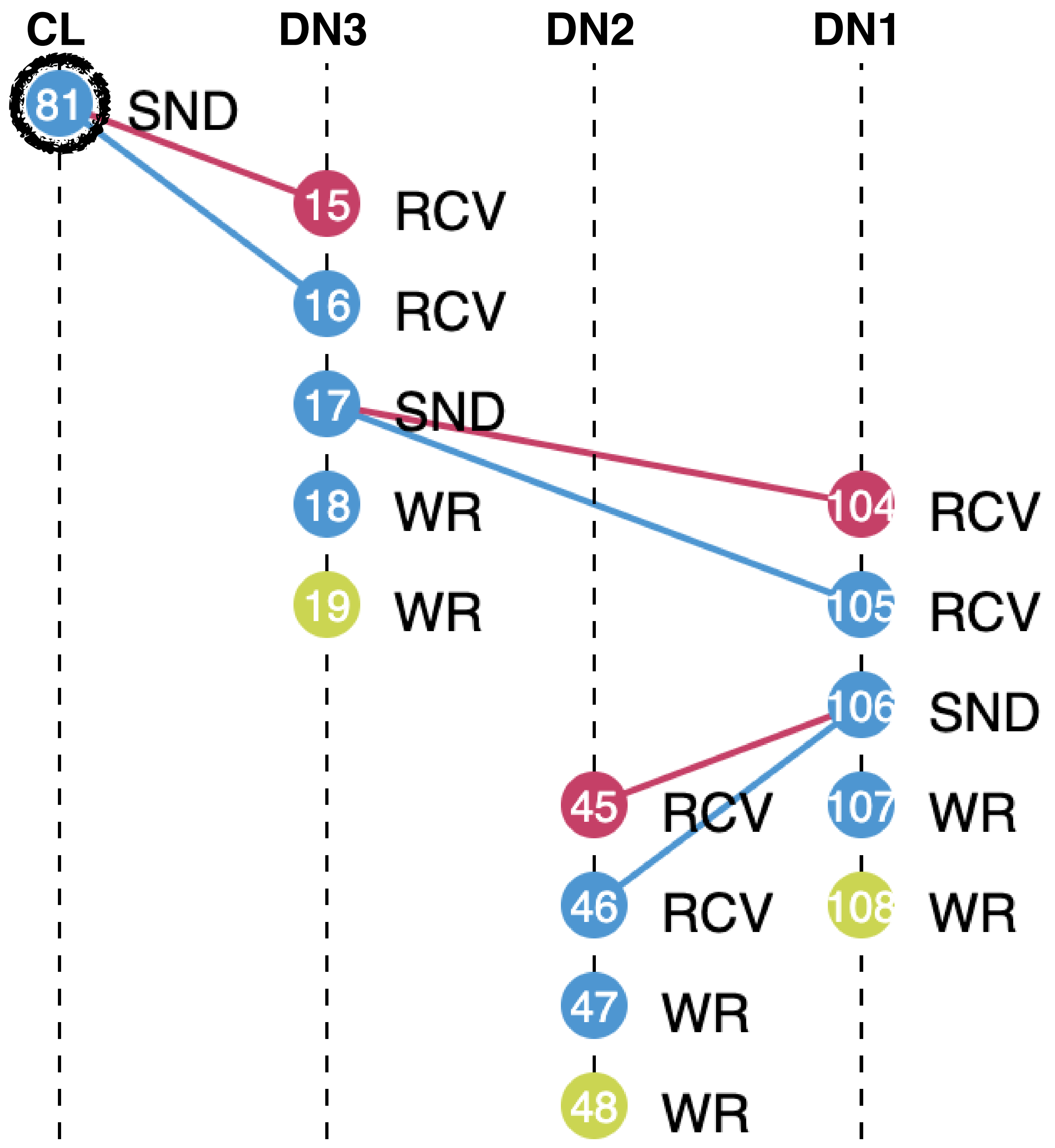

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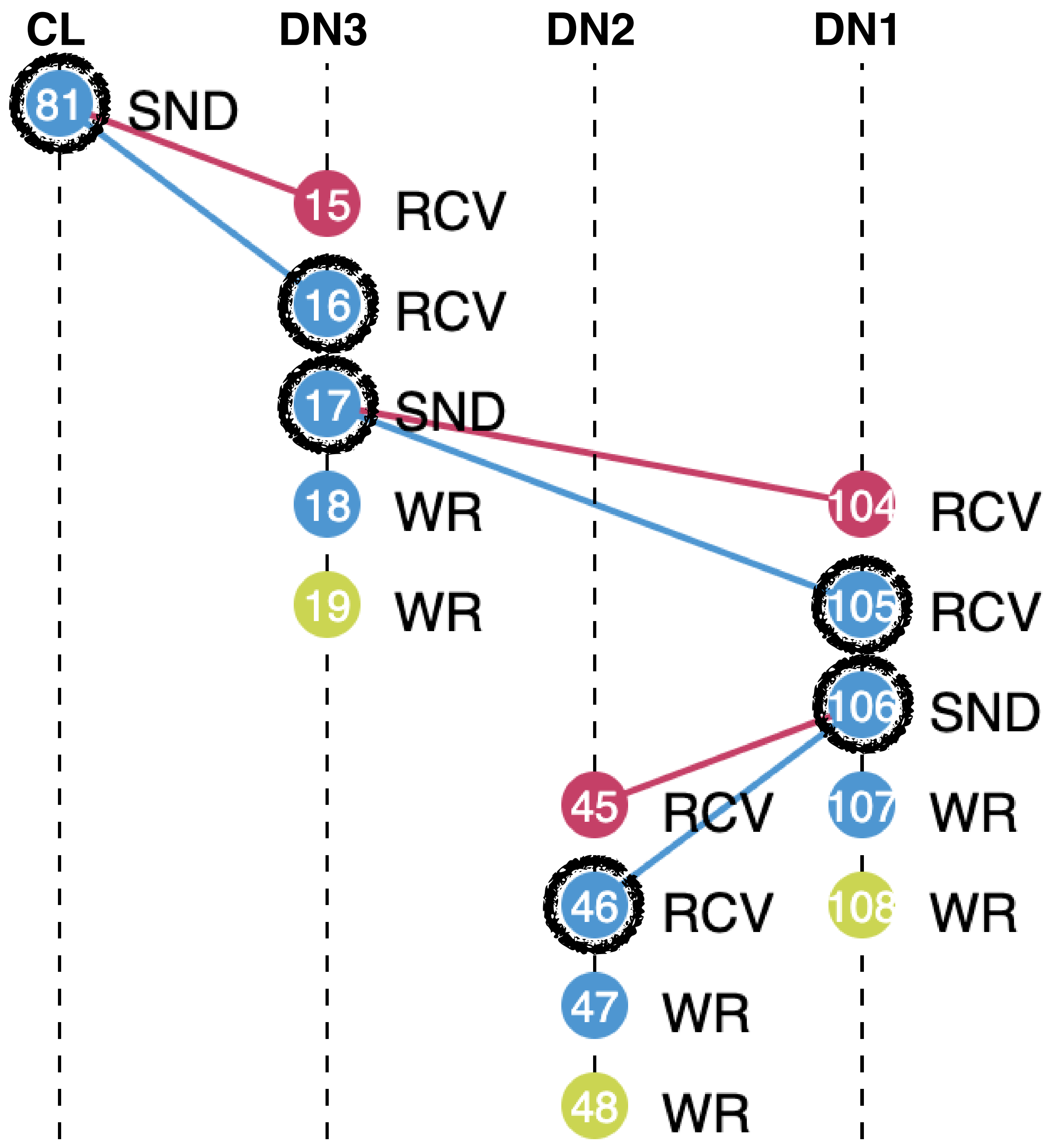

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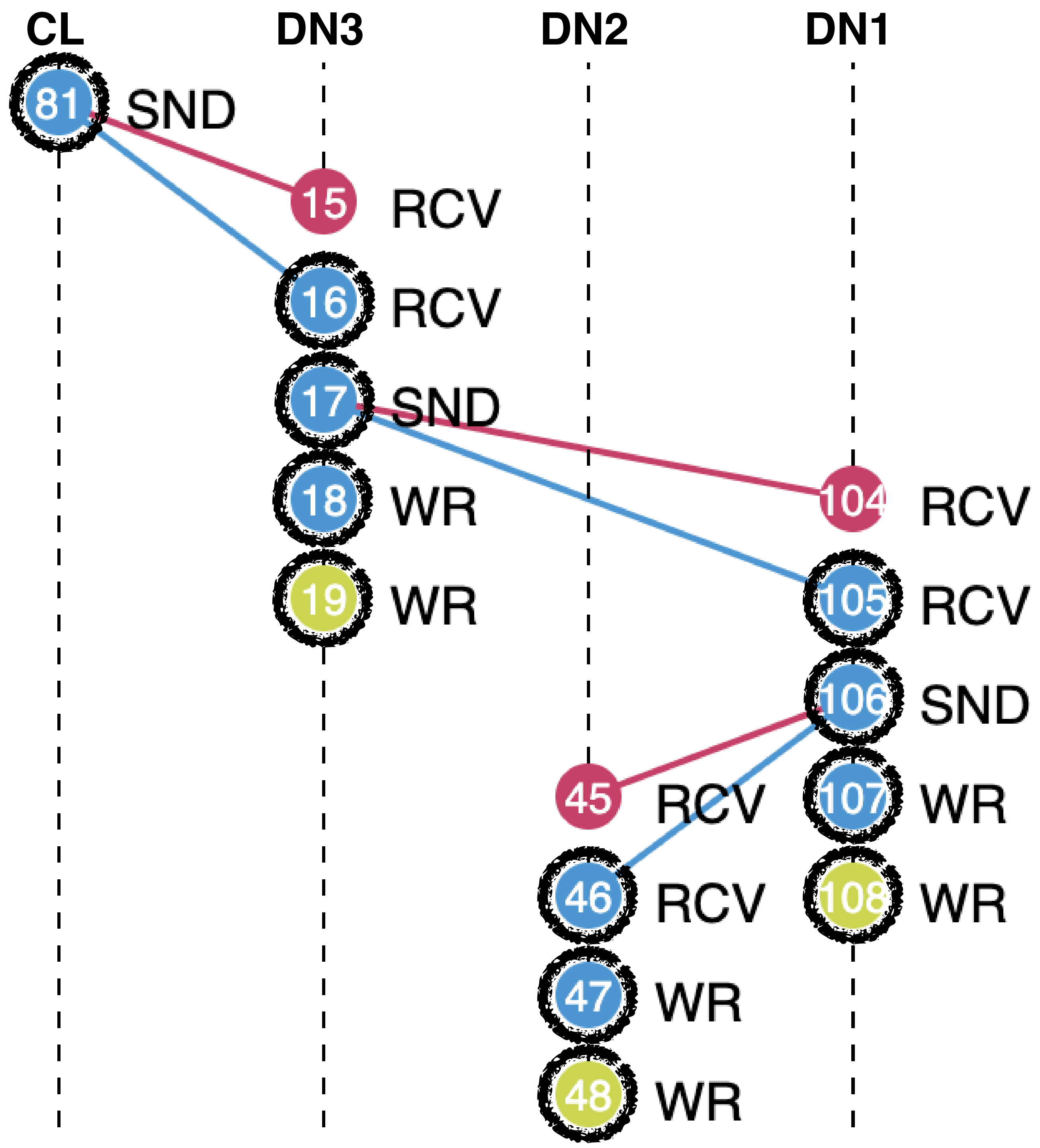

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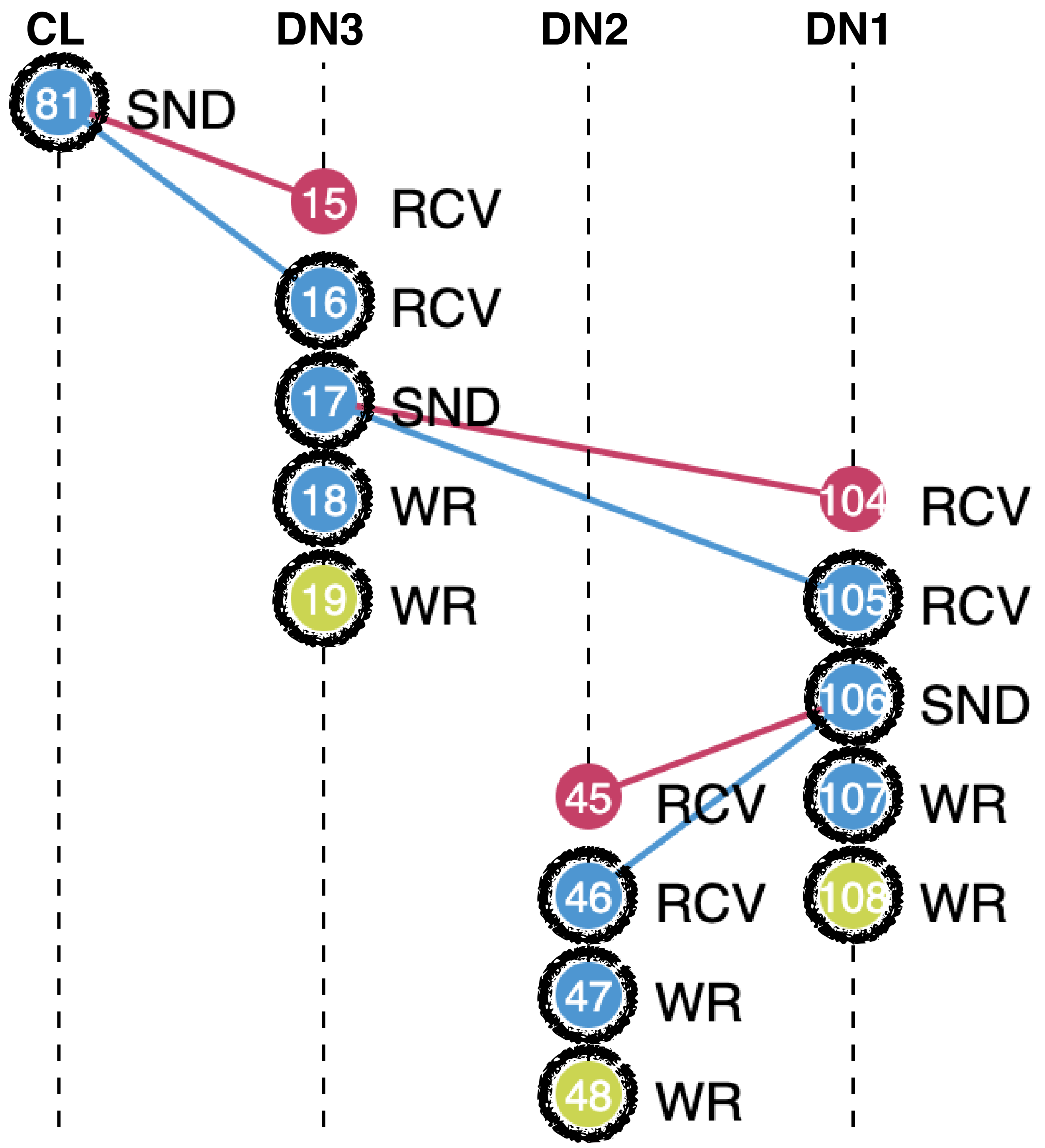

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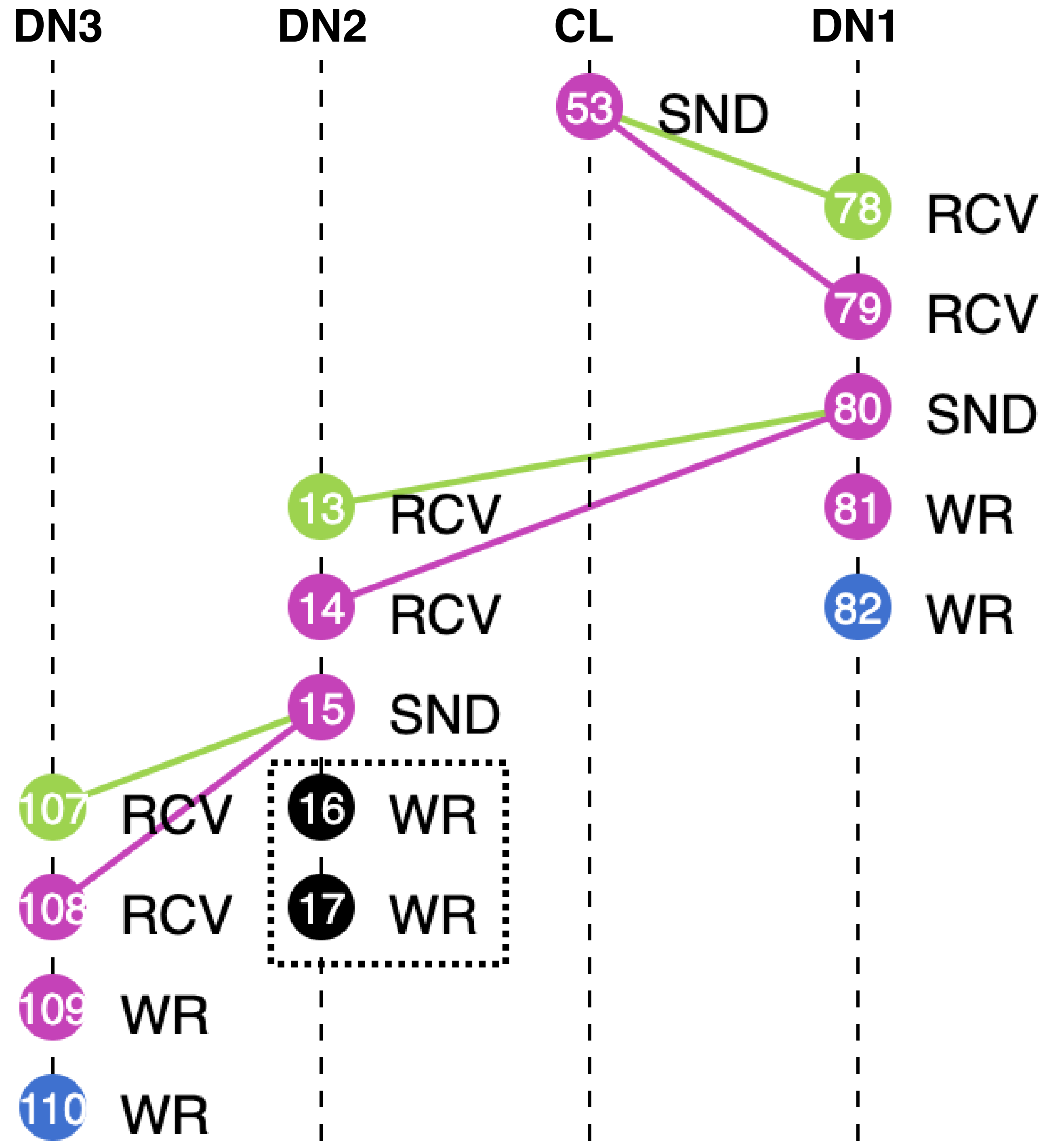

b) Storage corruption

Data persisted by DataNode 2 differs from clients' data

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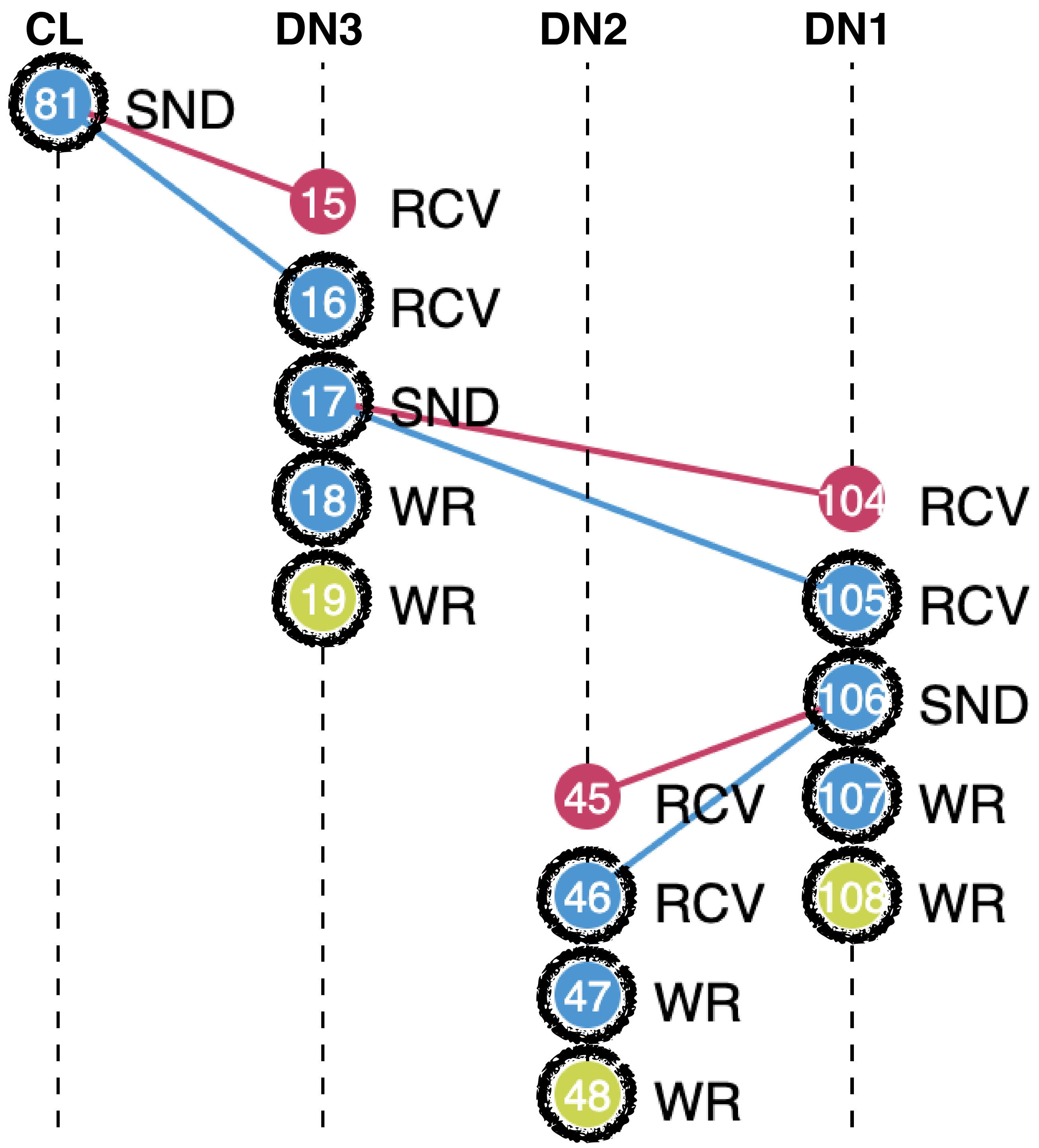

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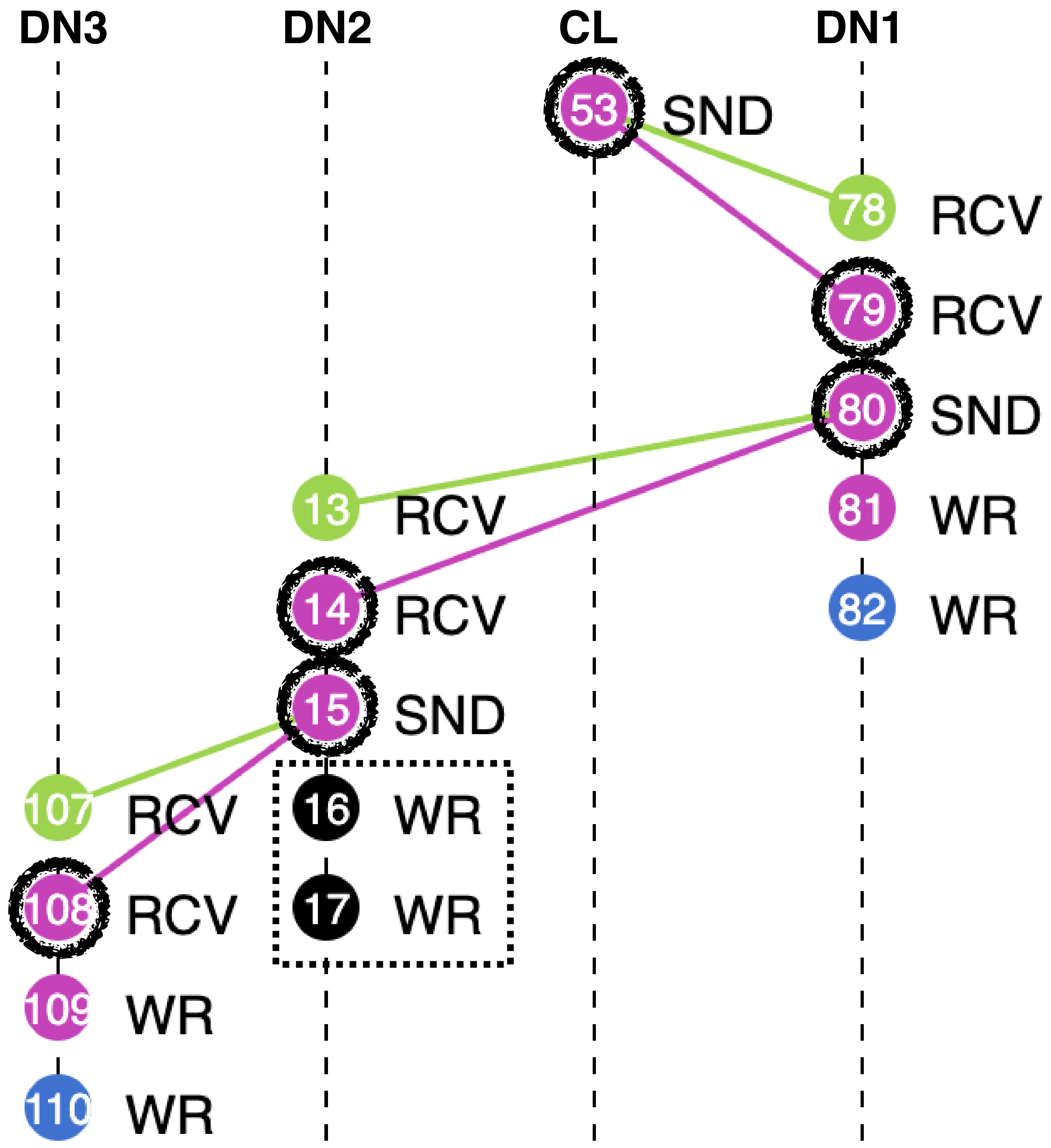

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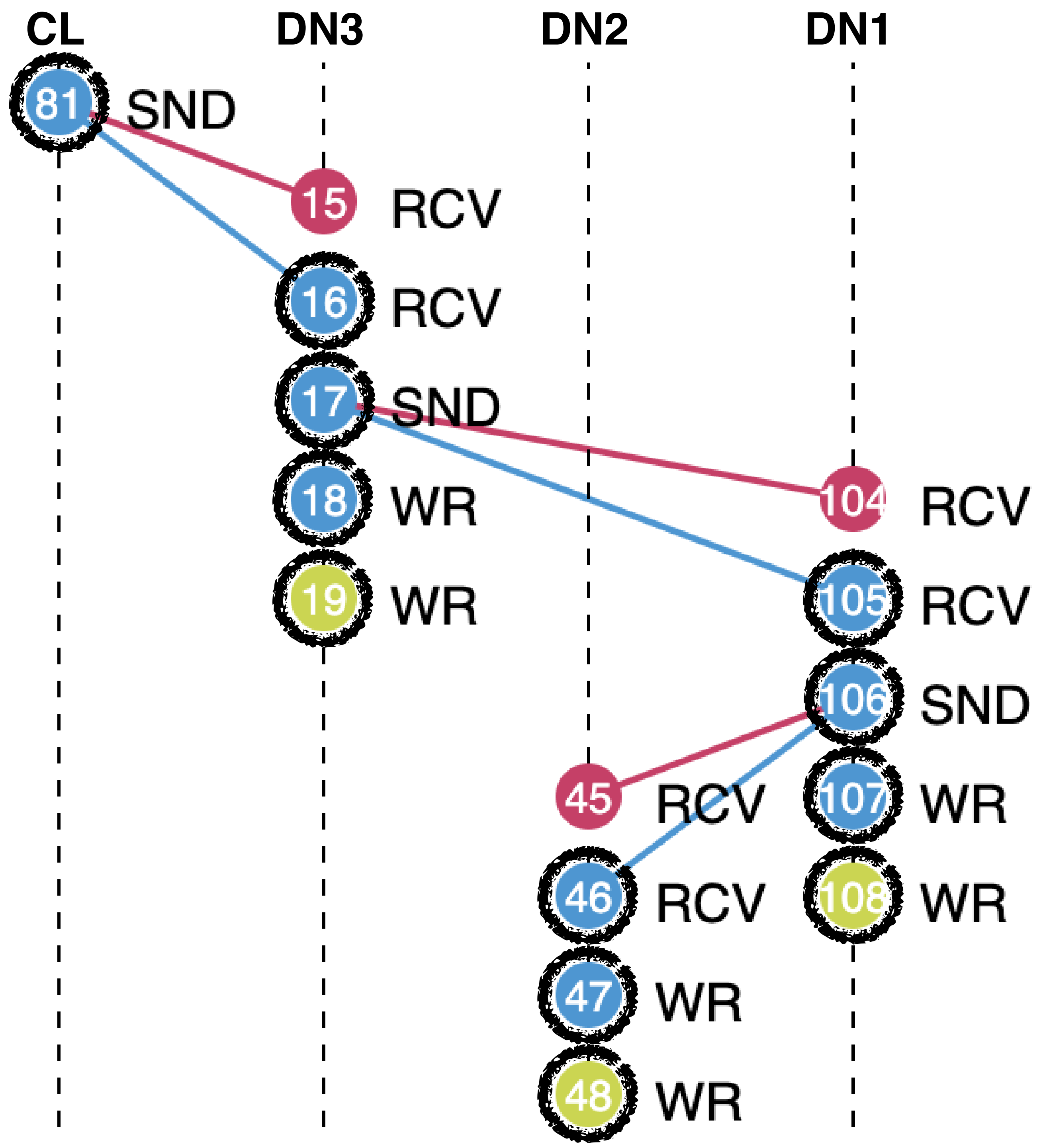

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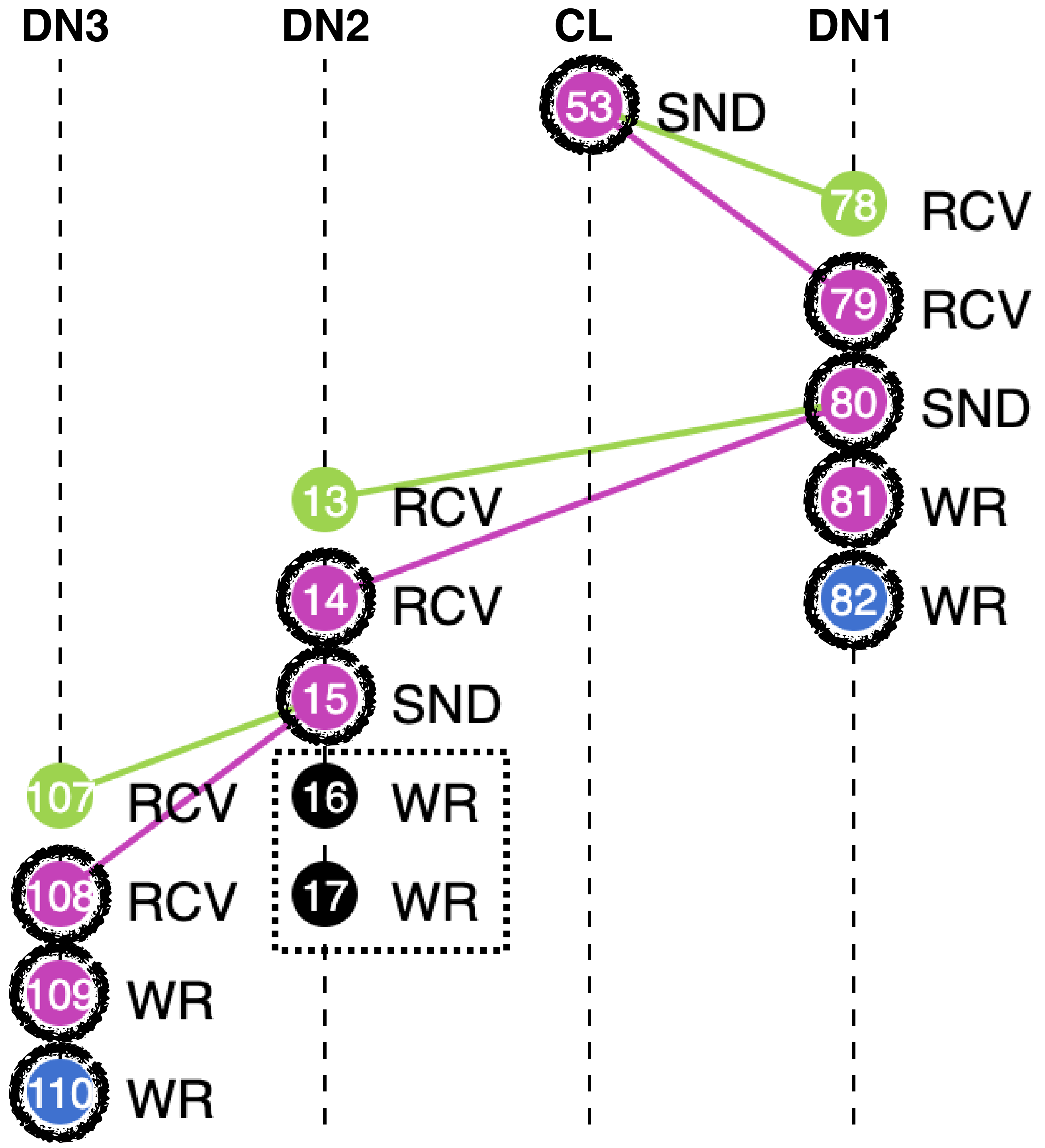

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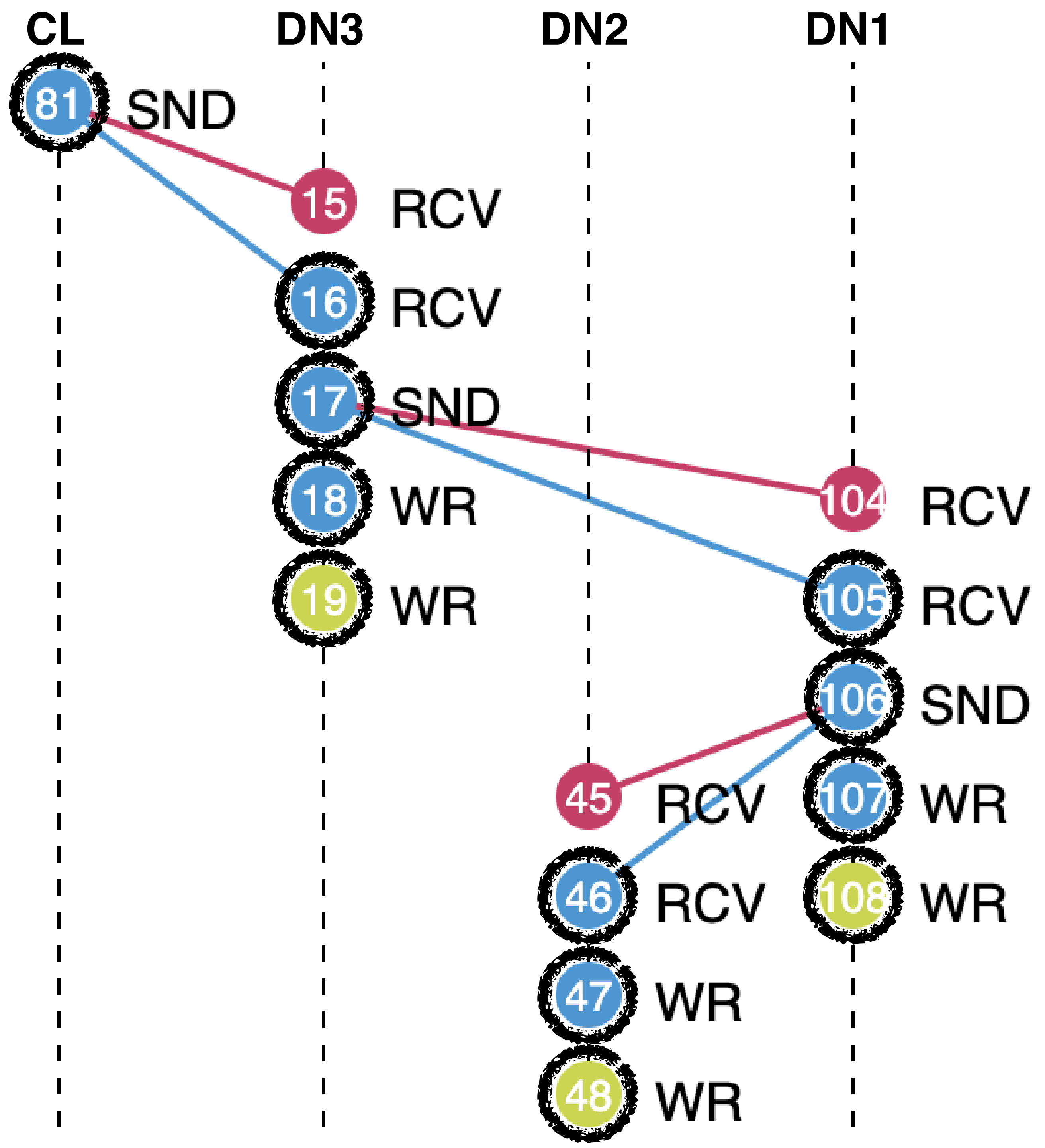

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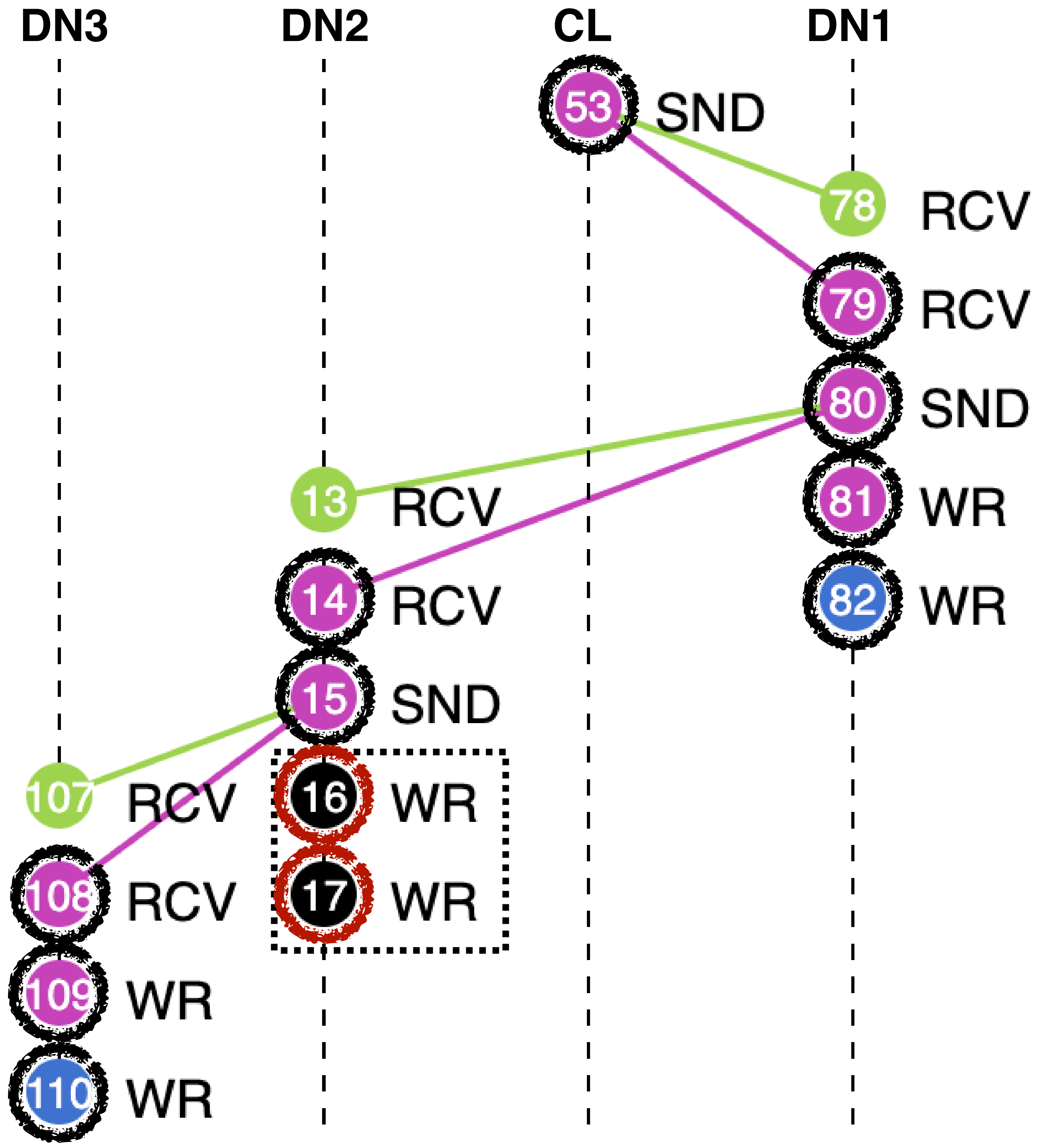

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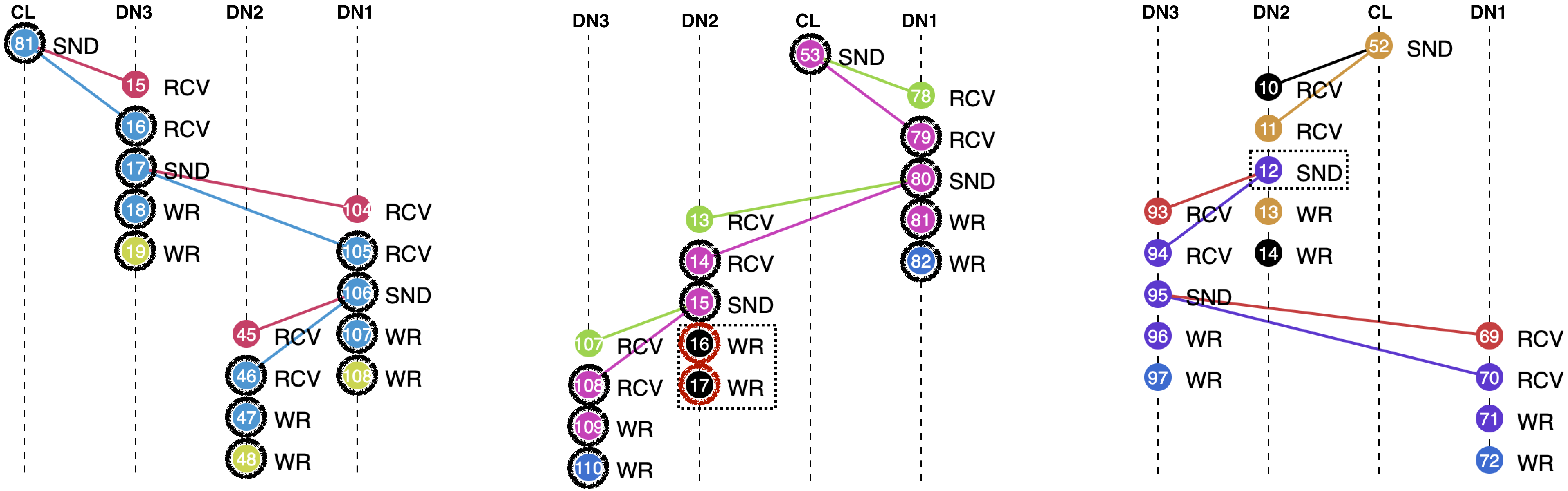

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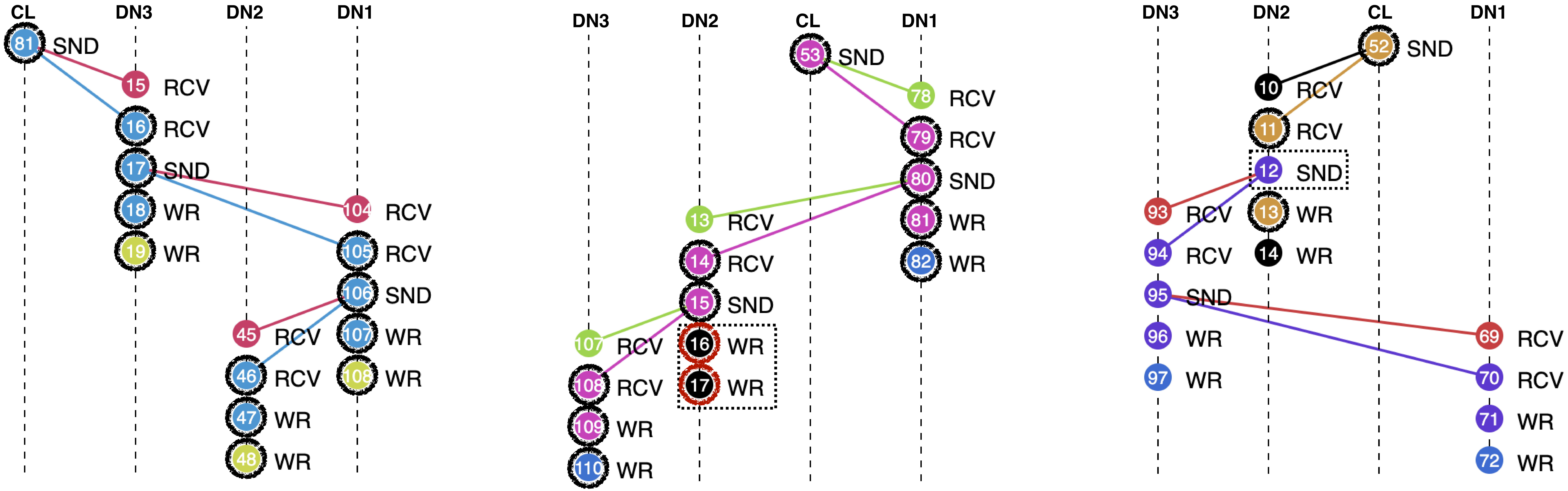

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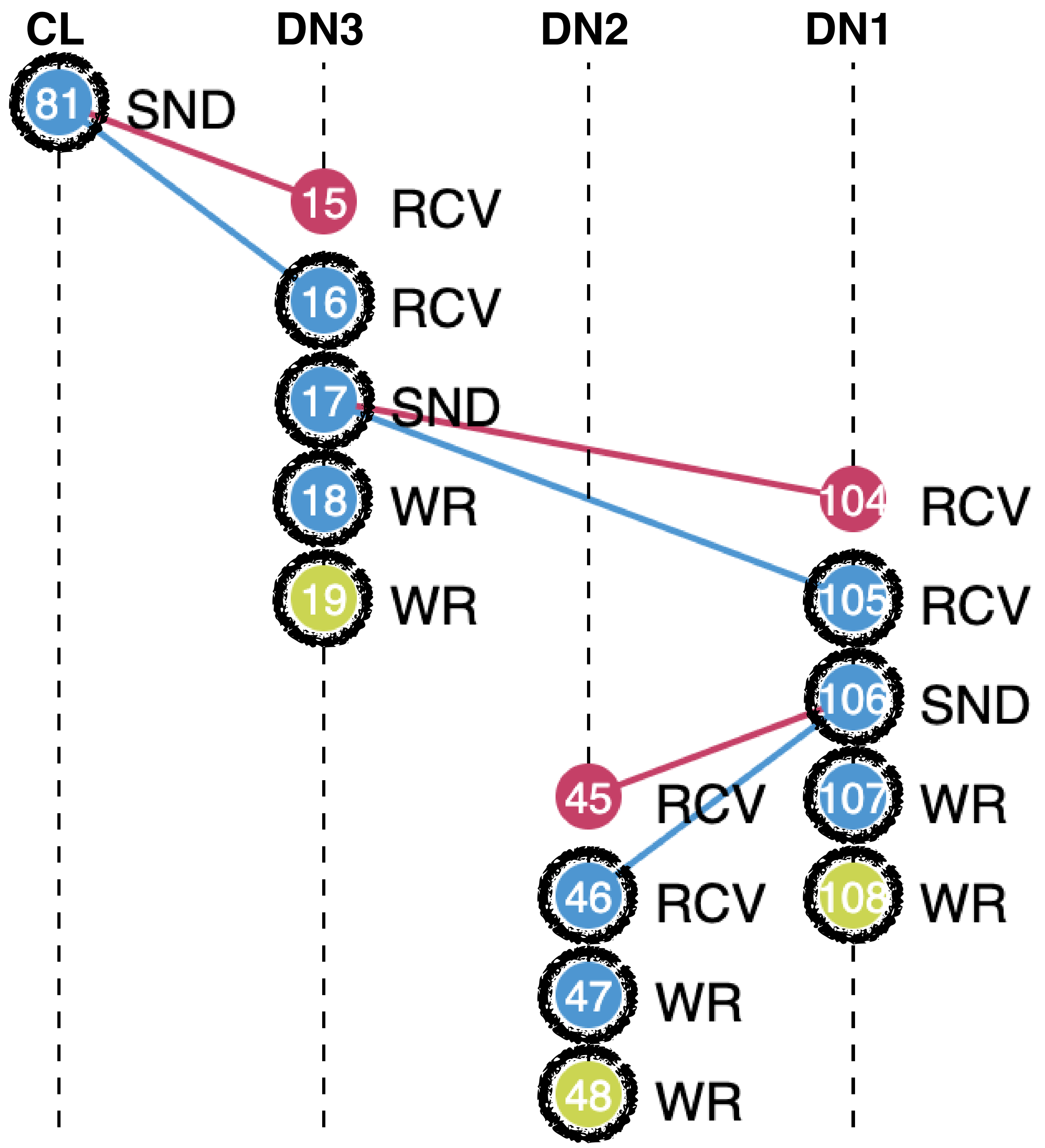

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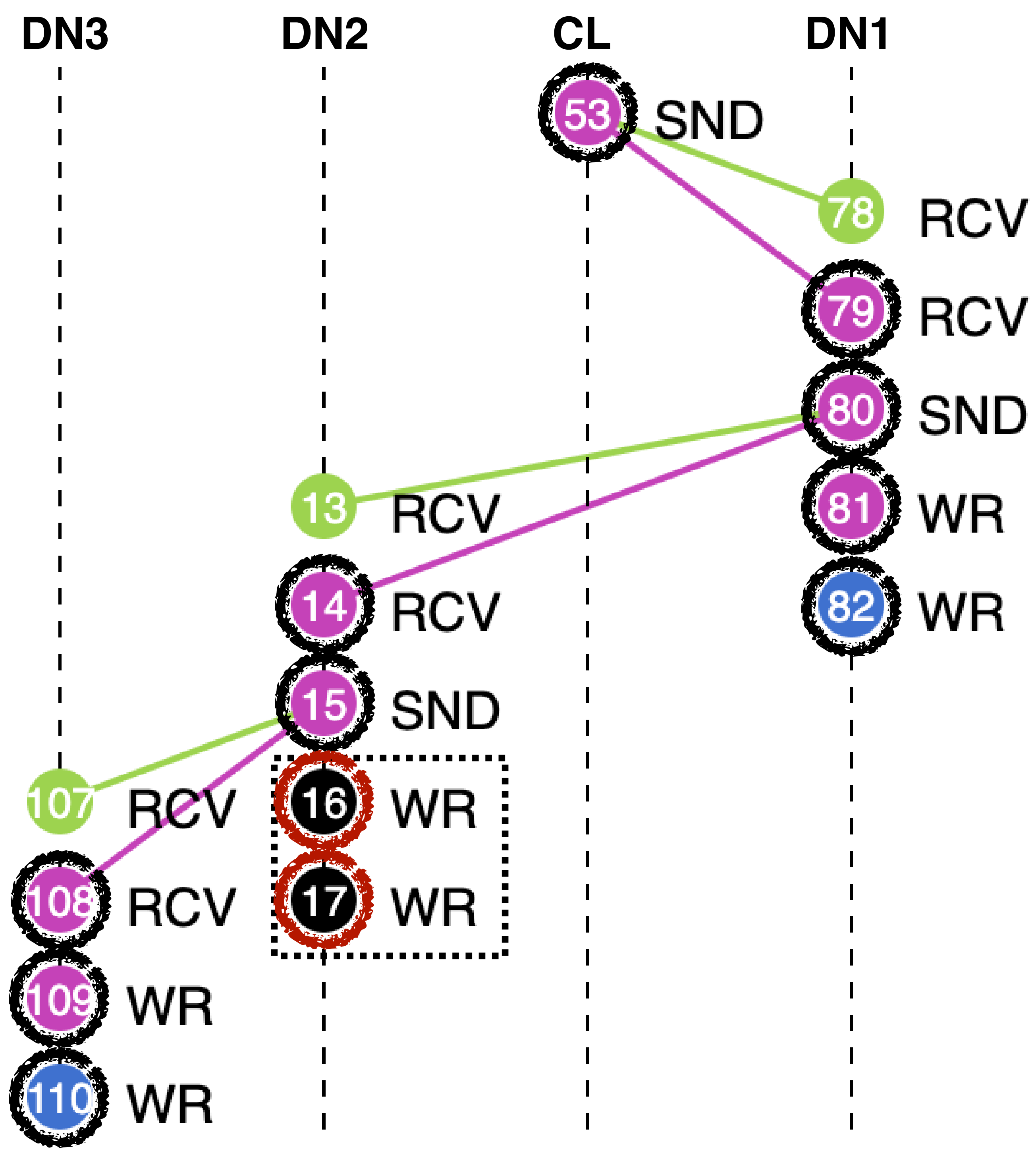

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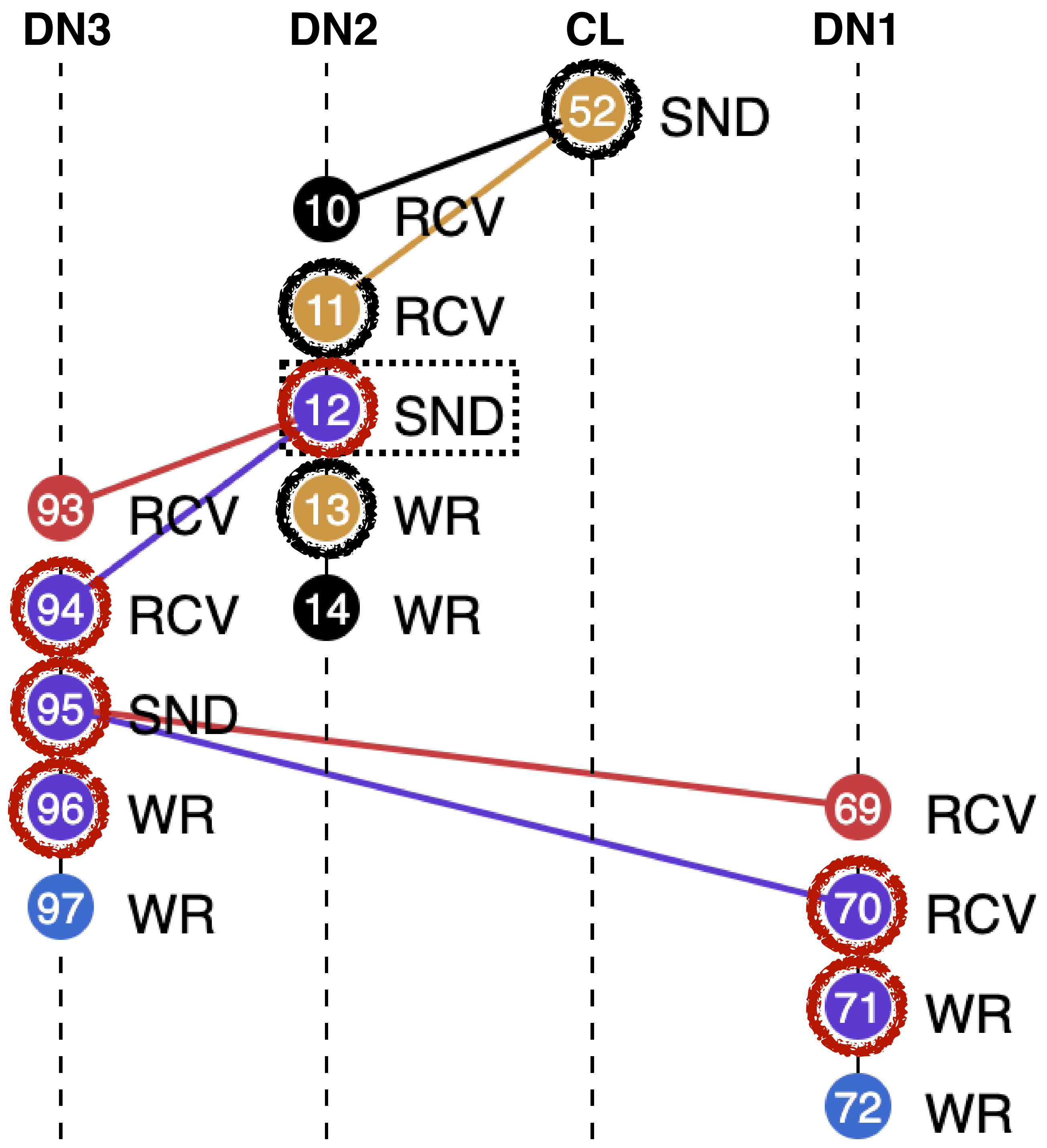

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CaT Summary

- CaT's content-aware approach enables the detection of **data adulteration, corruption and leakage patterns** that would go **unnoticed with state-of-the-art context-based** solutions

- **Open challenges**:
  - Comprehensive diagnosis of applications
  - Practical and efficient analysis pipeline

Comprehensive and Flexible Diagnosis

DIO, a generic tool for diagnosing applications’ storage I/O

- Supports 42 storage-related system calls
- Collects their type, arguments, return value and extra context from the kernel
- Provides different strategies to customize the amount and detail of collected data
- Includes an integrated pipeline for near real-time analysis and visualization

DIO Design

■ DIO’s components → DIO main flow ⇢ App flow

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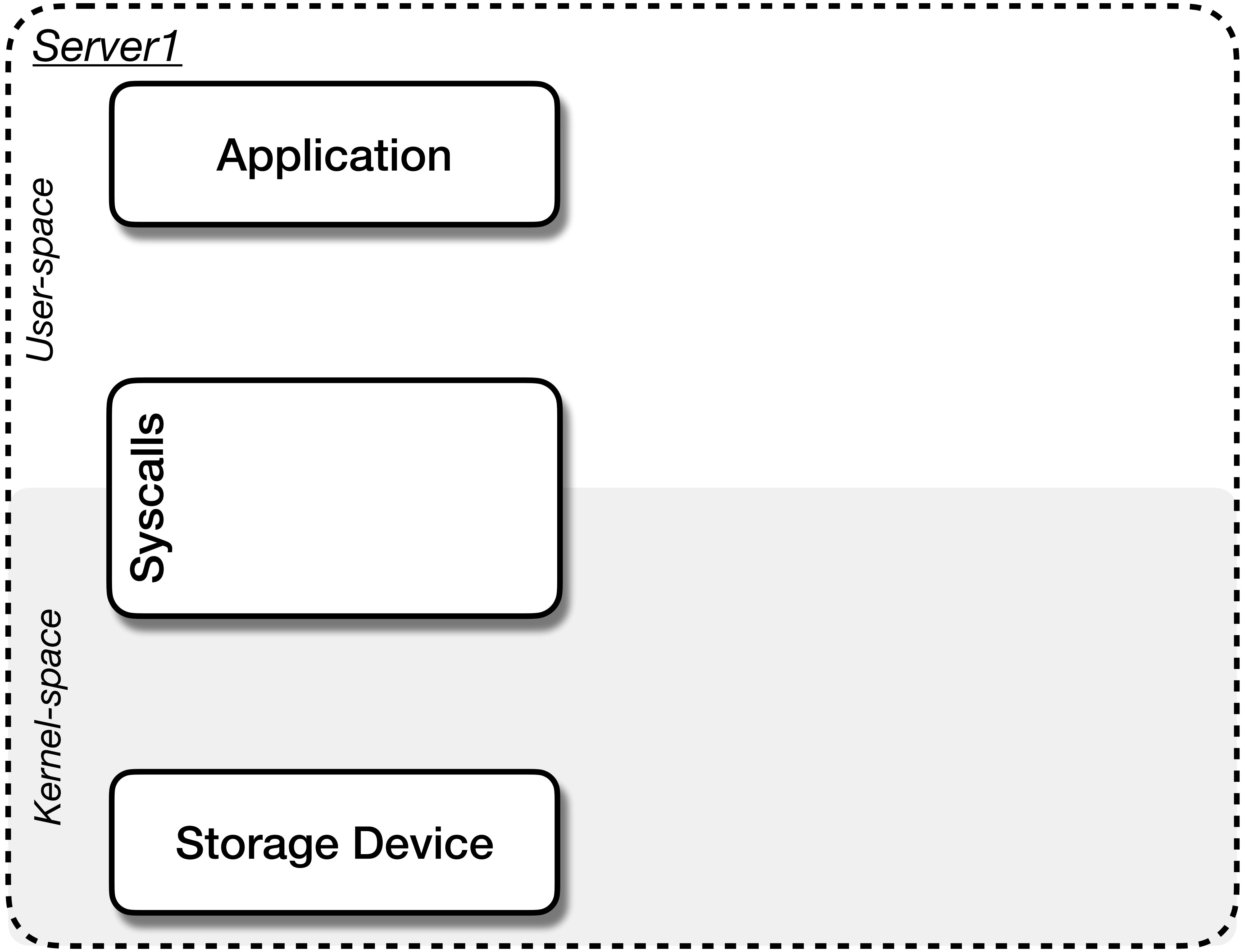

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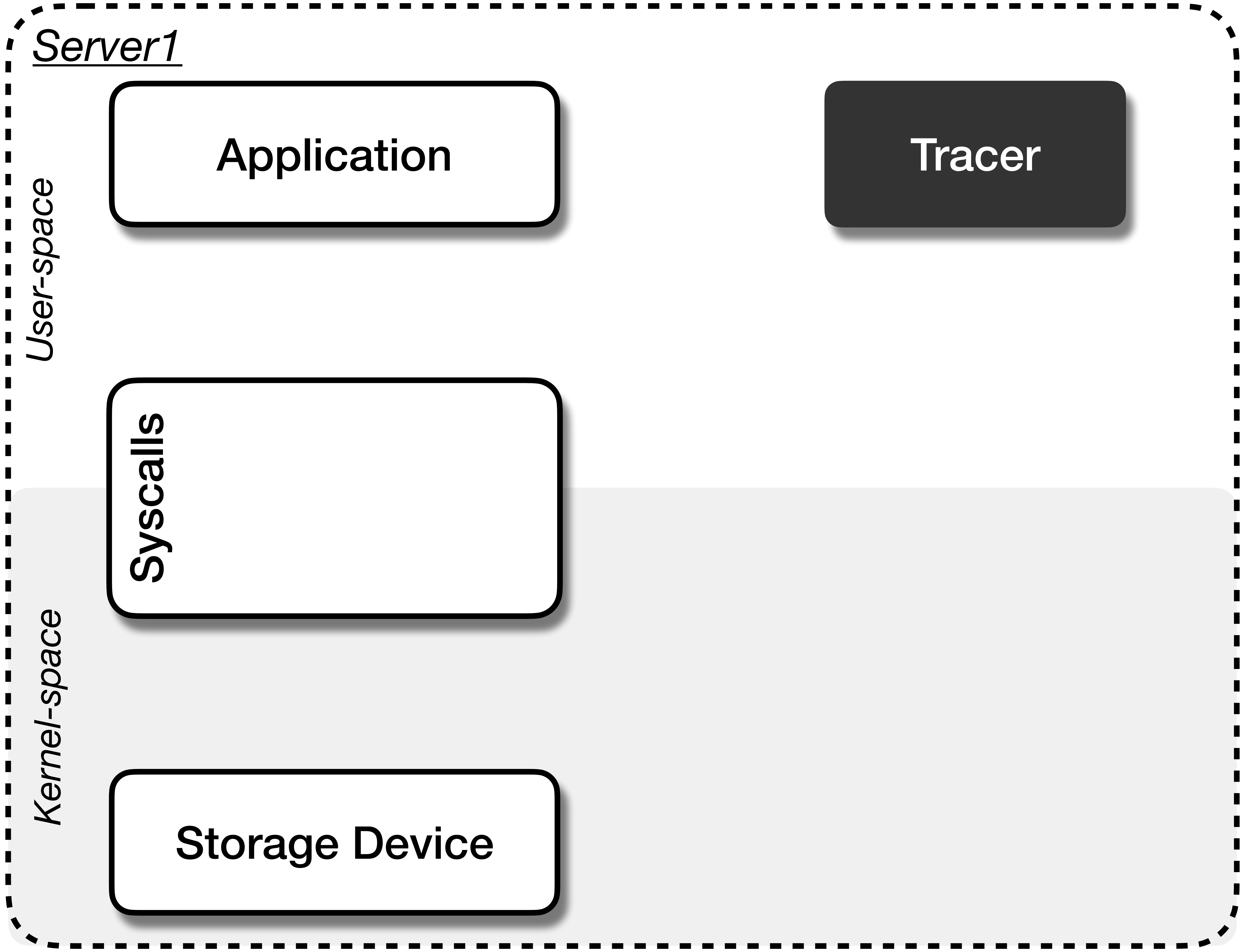

DIO’s tracer runs along the targeted application, intercepting its syscalls

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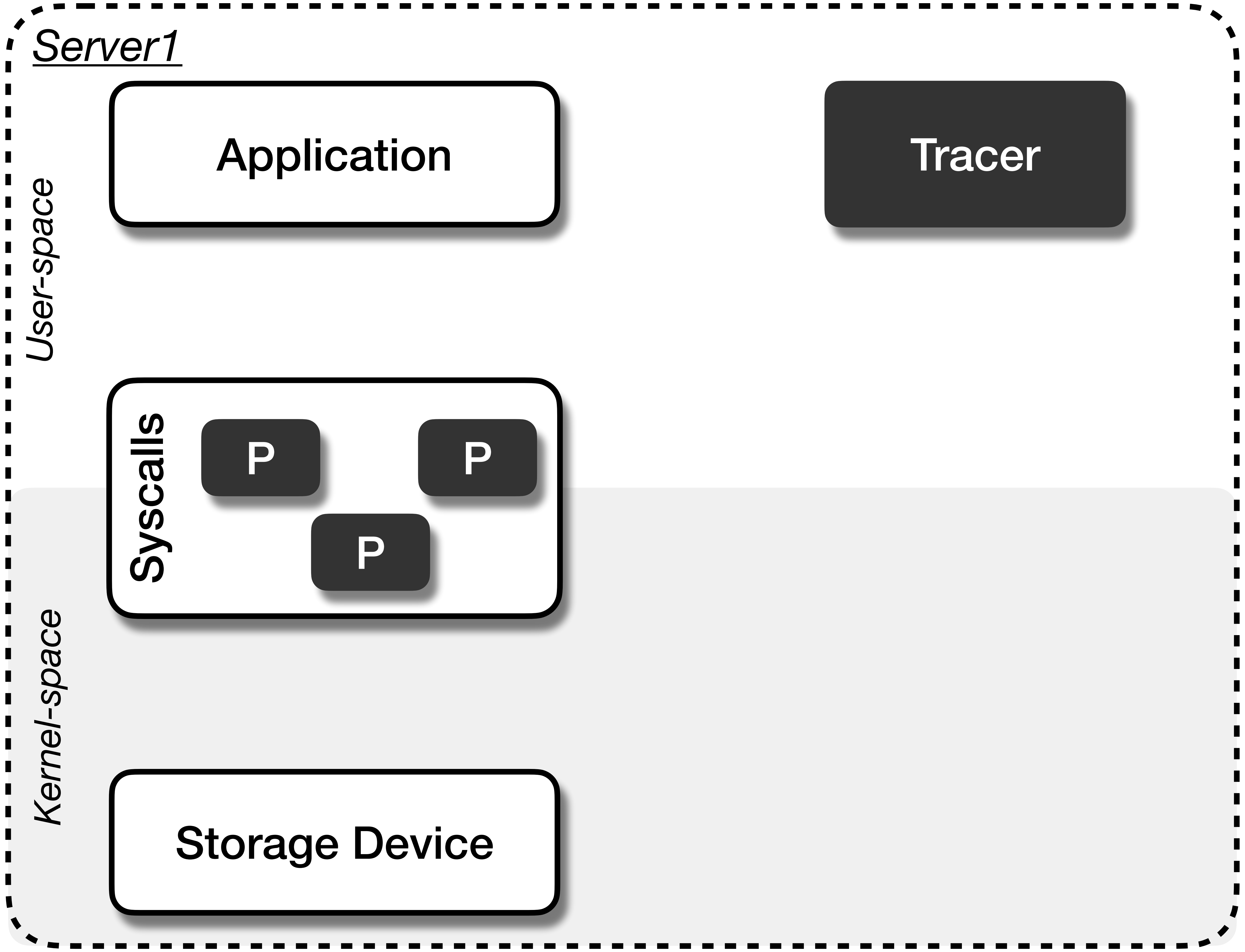

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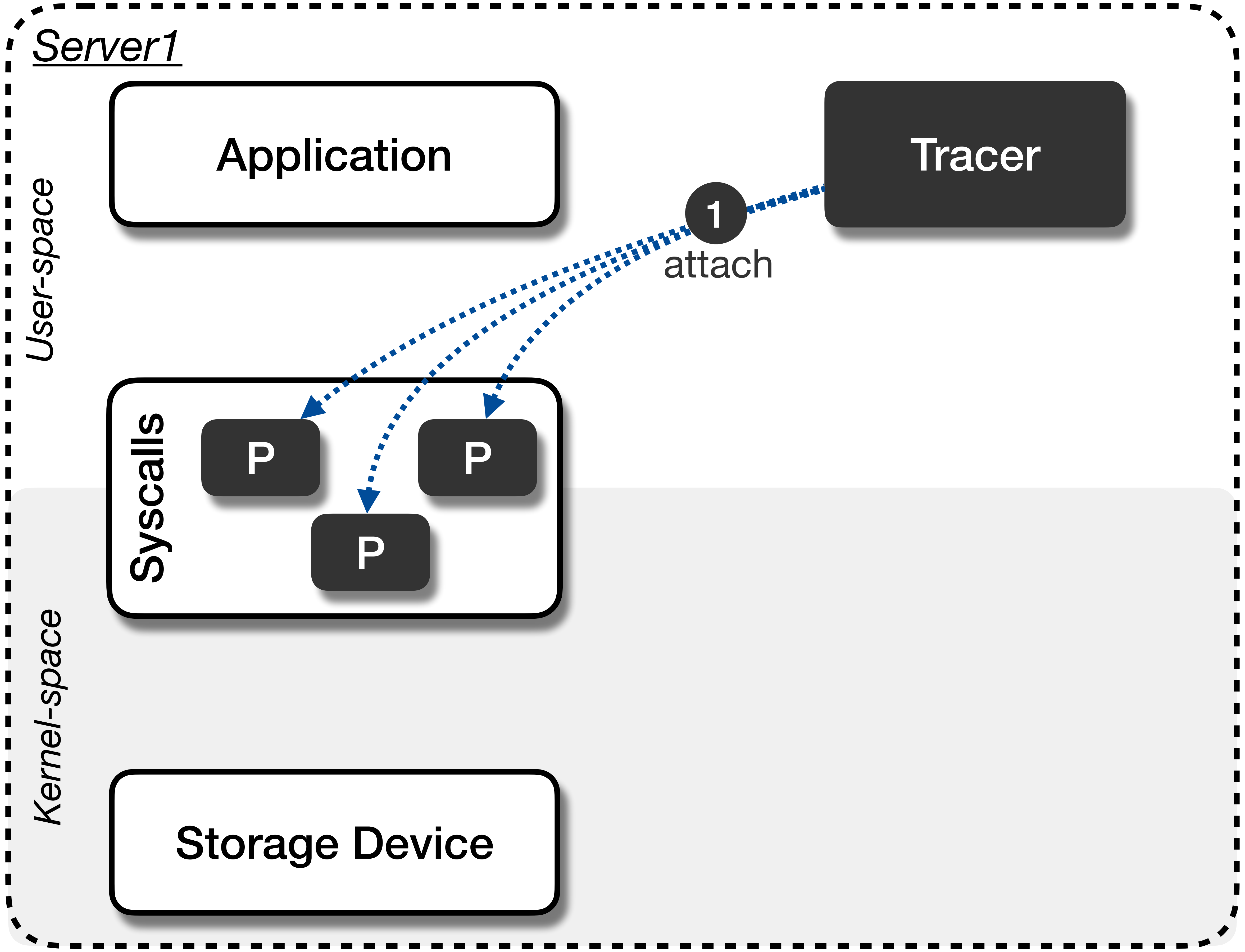

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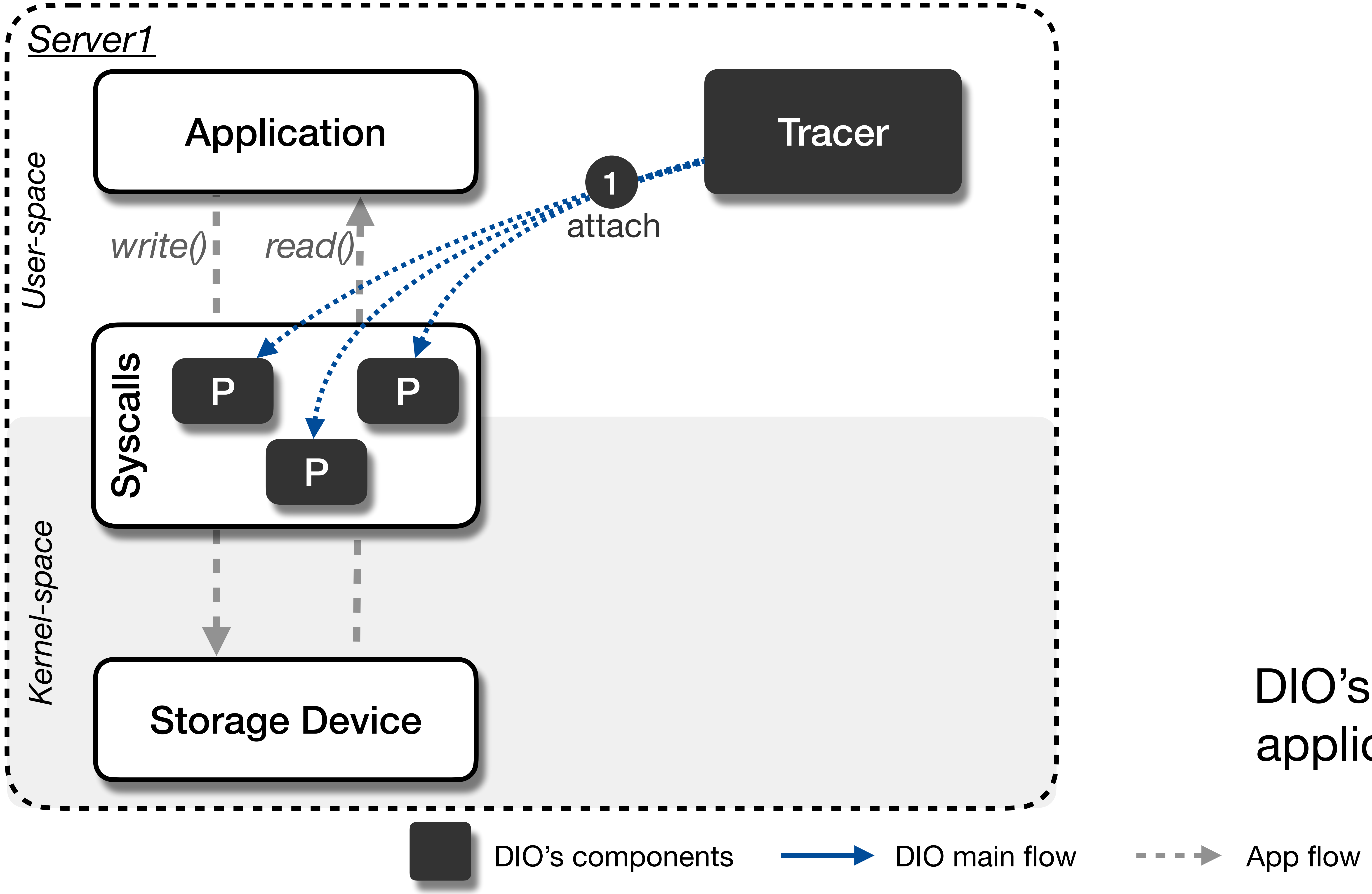

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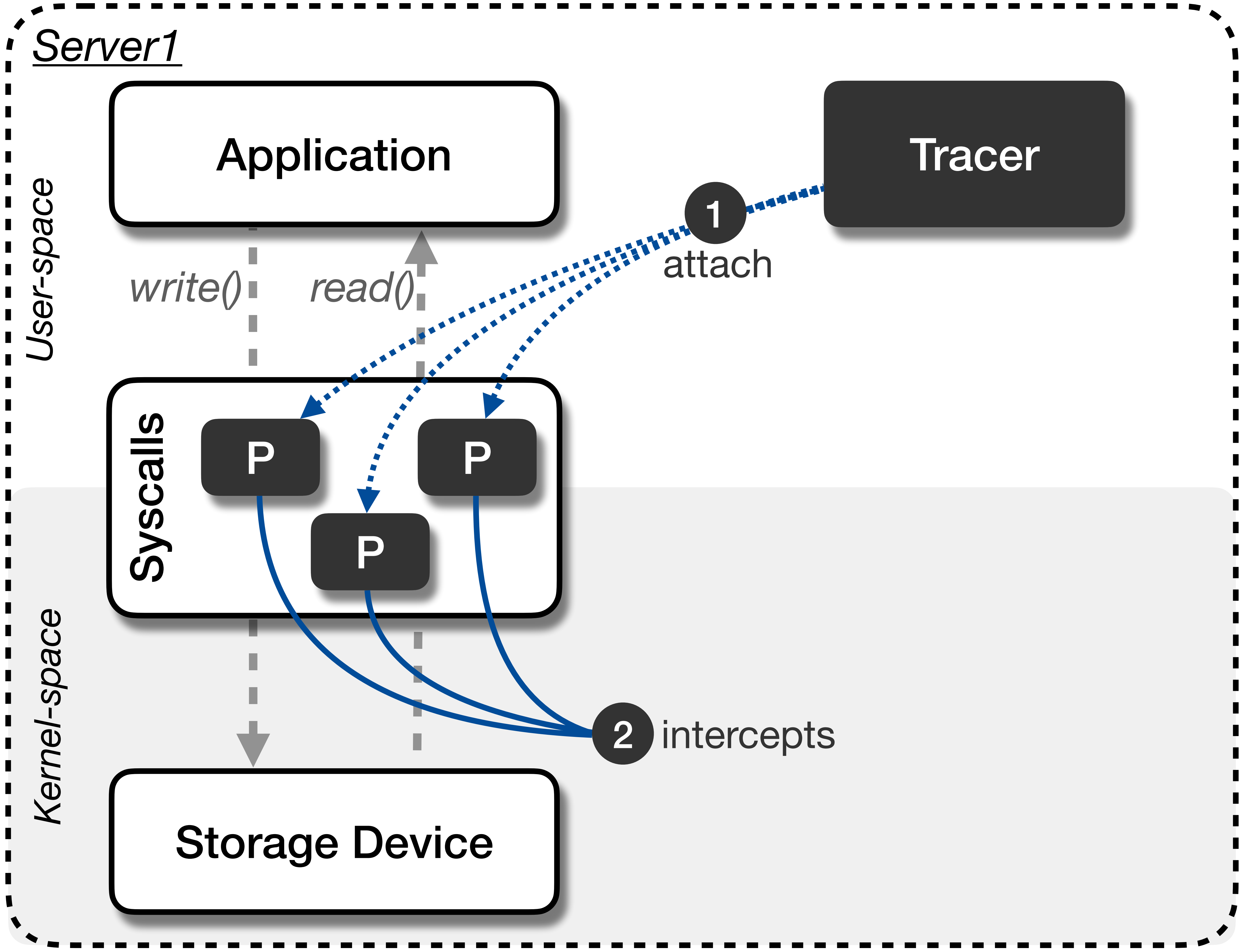

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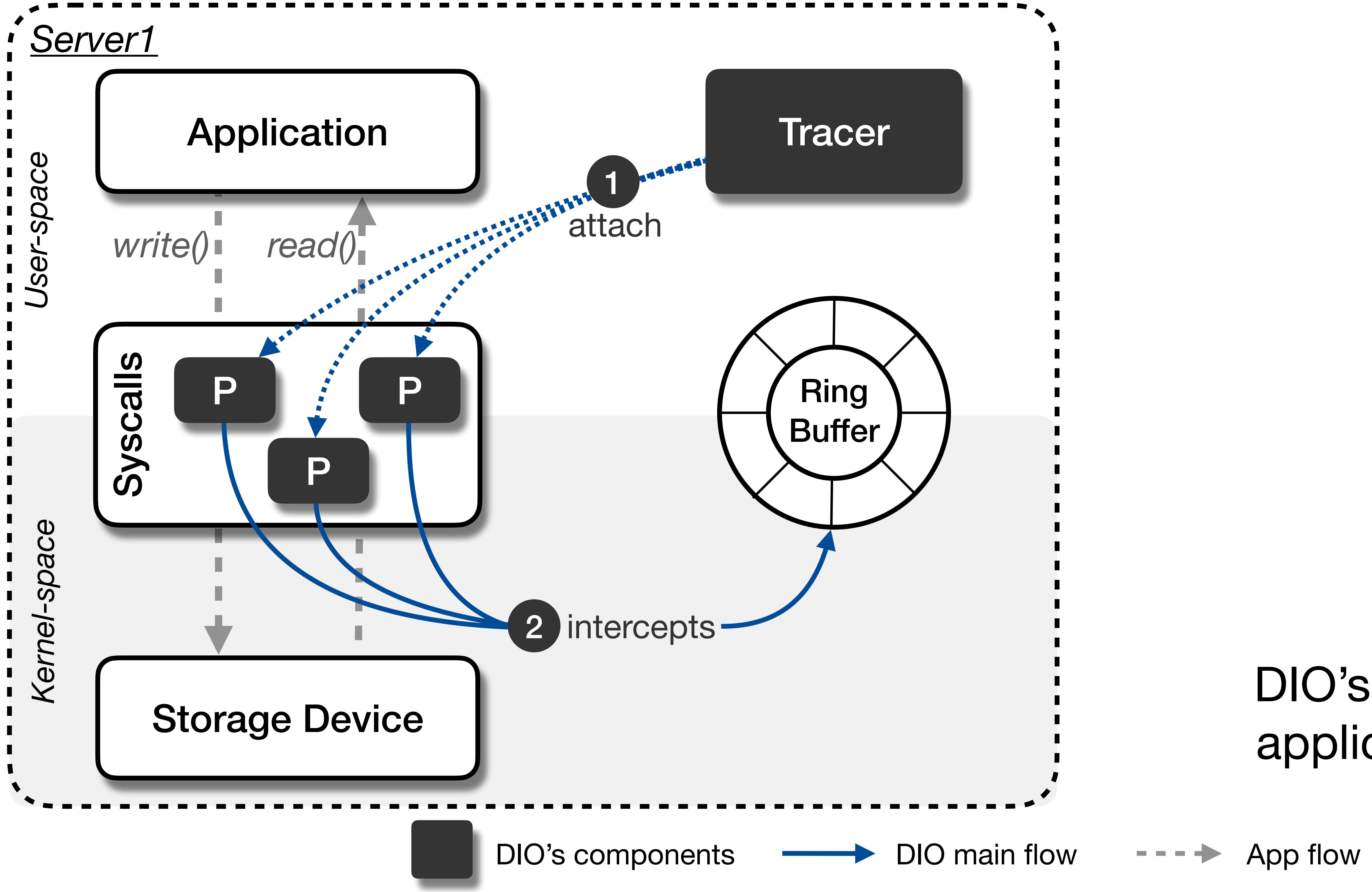

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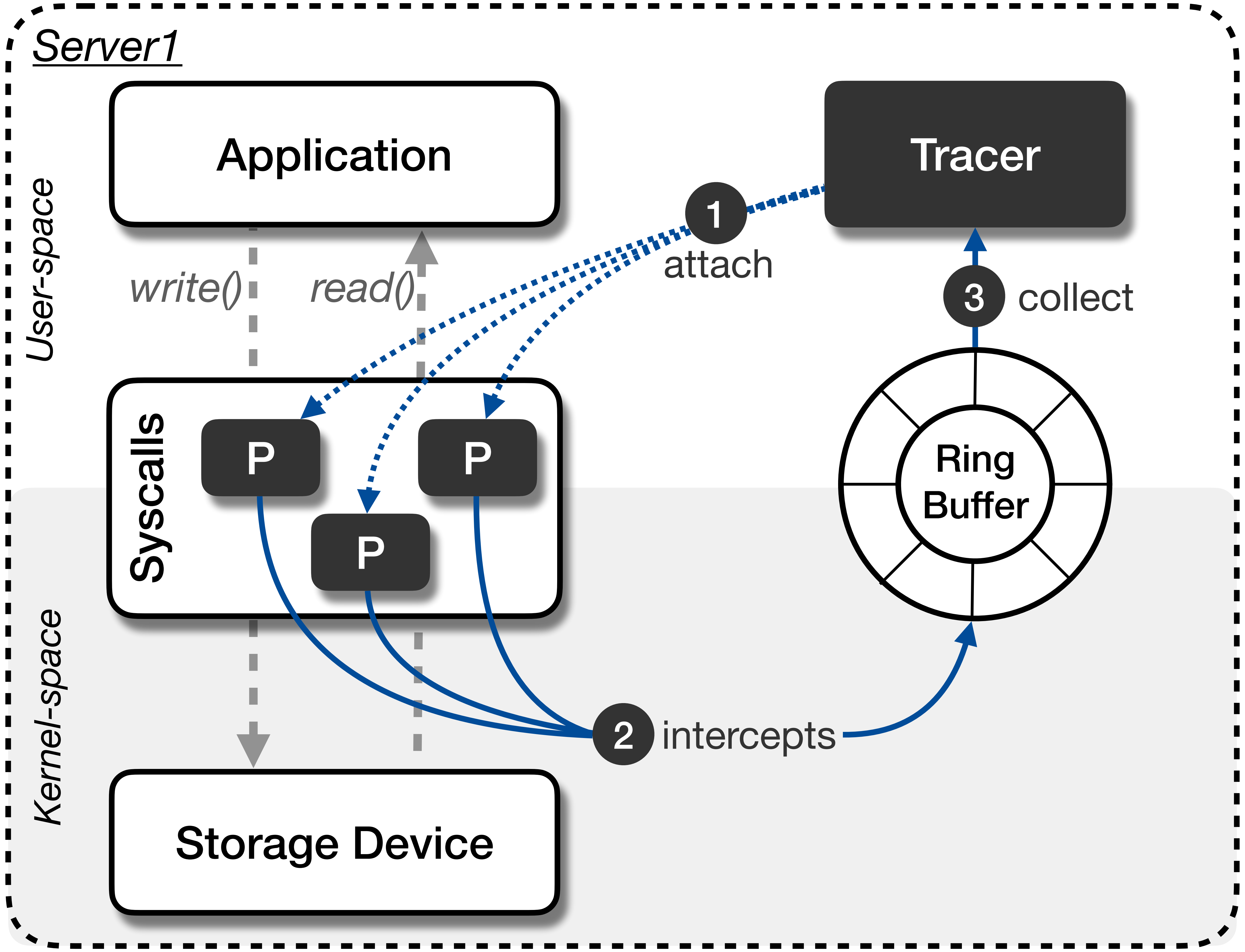

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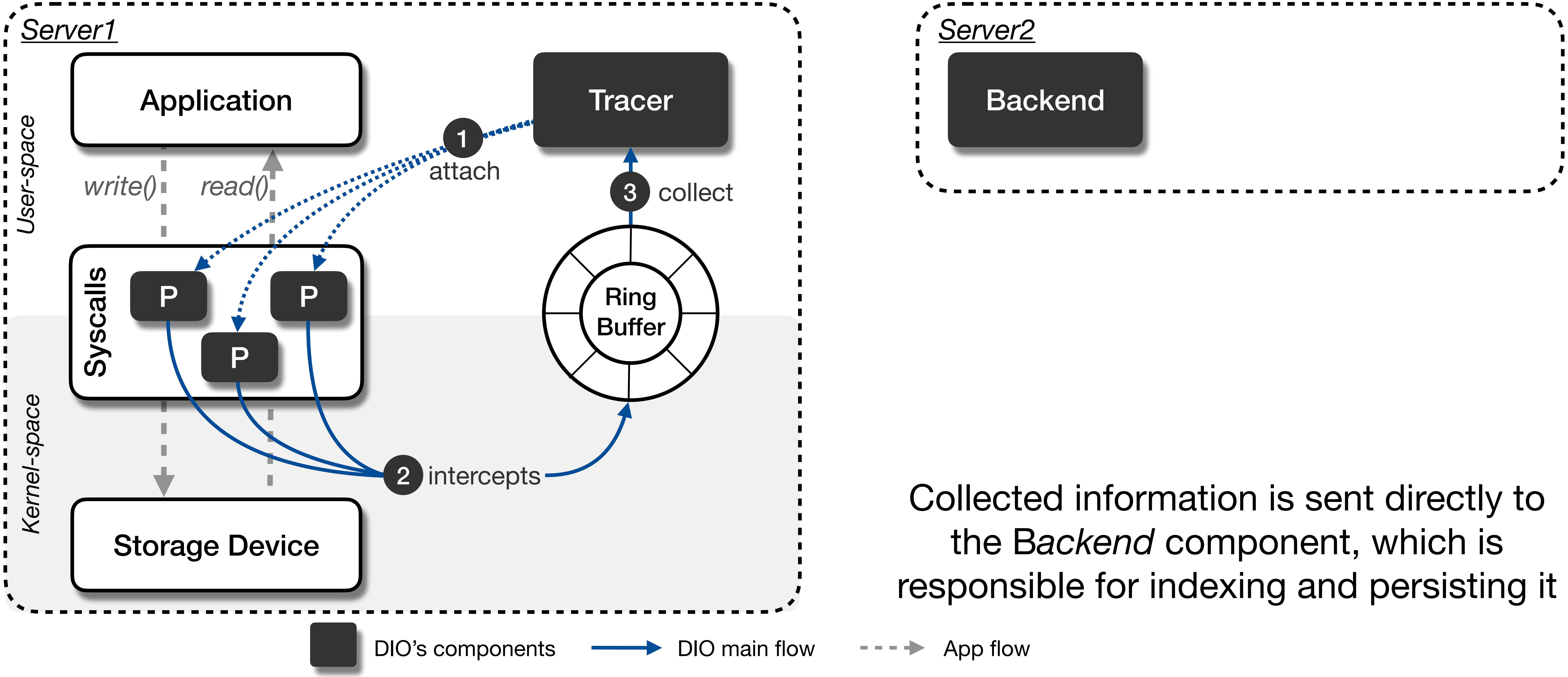

Collected information is sent directly to the *Backend* component, which is responsible for indexing and persisting it

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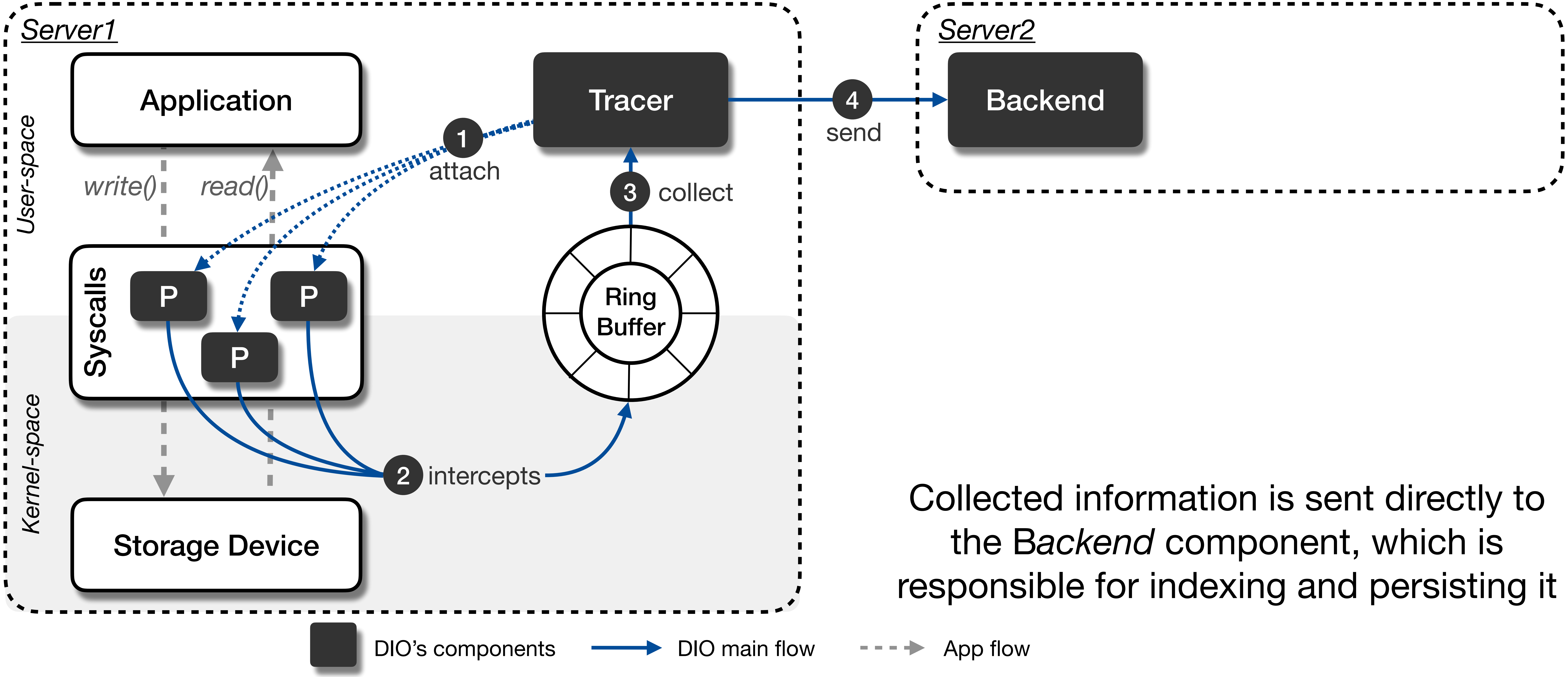

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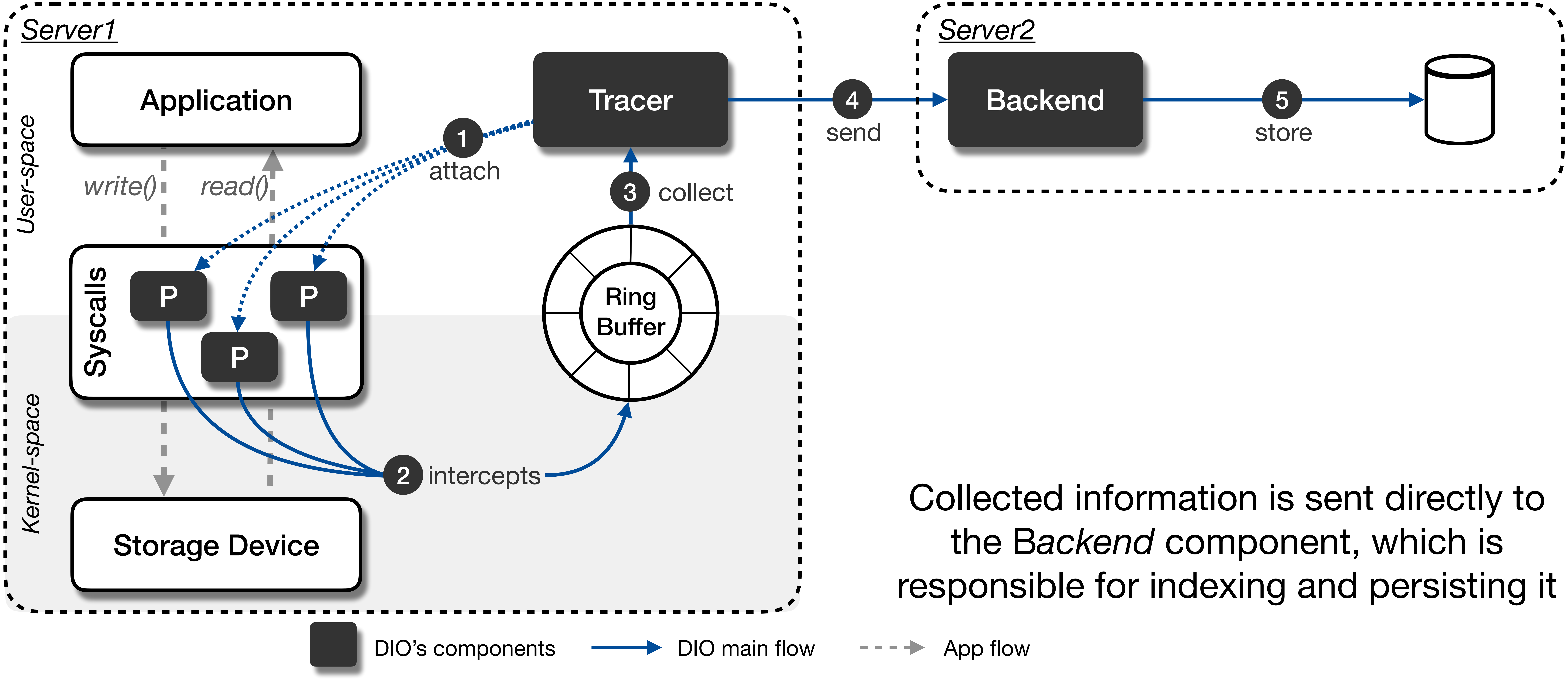

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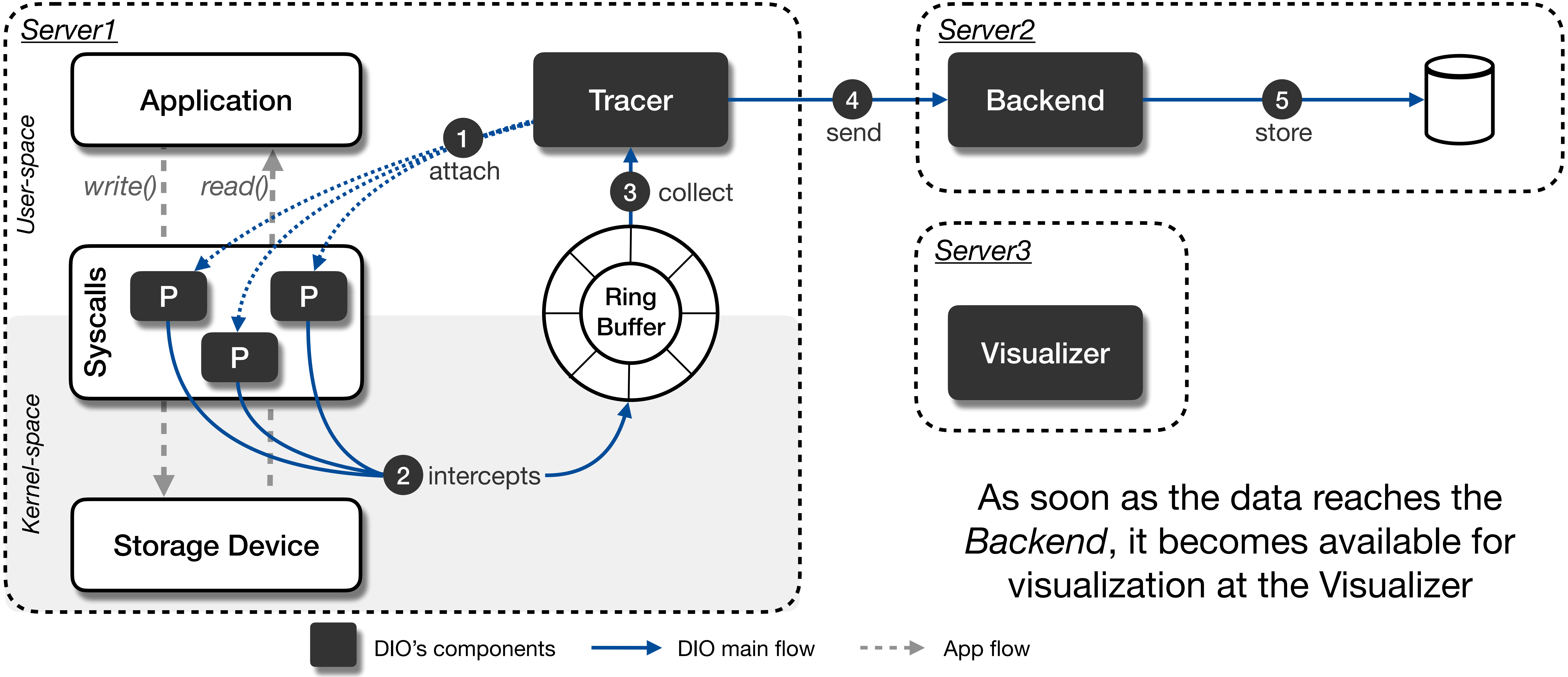

As soon as the data reaches the *Backend*, it becomes available for visualization at the Visualizer

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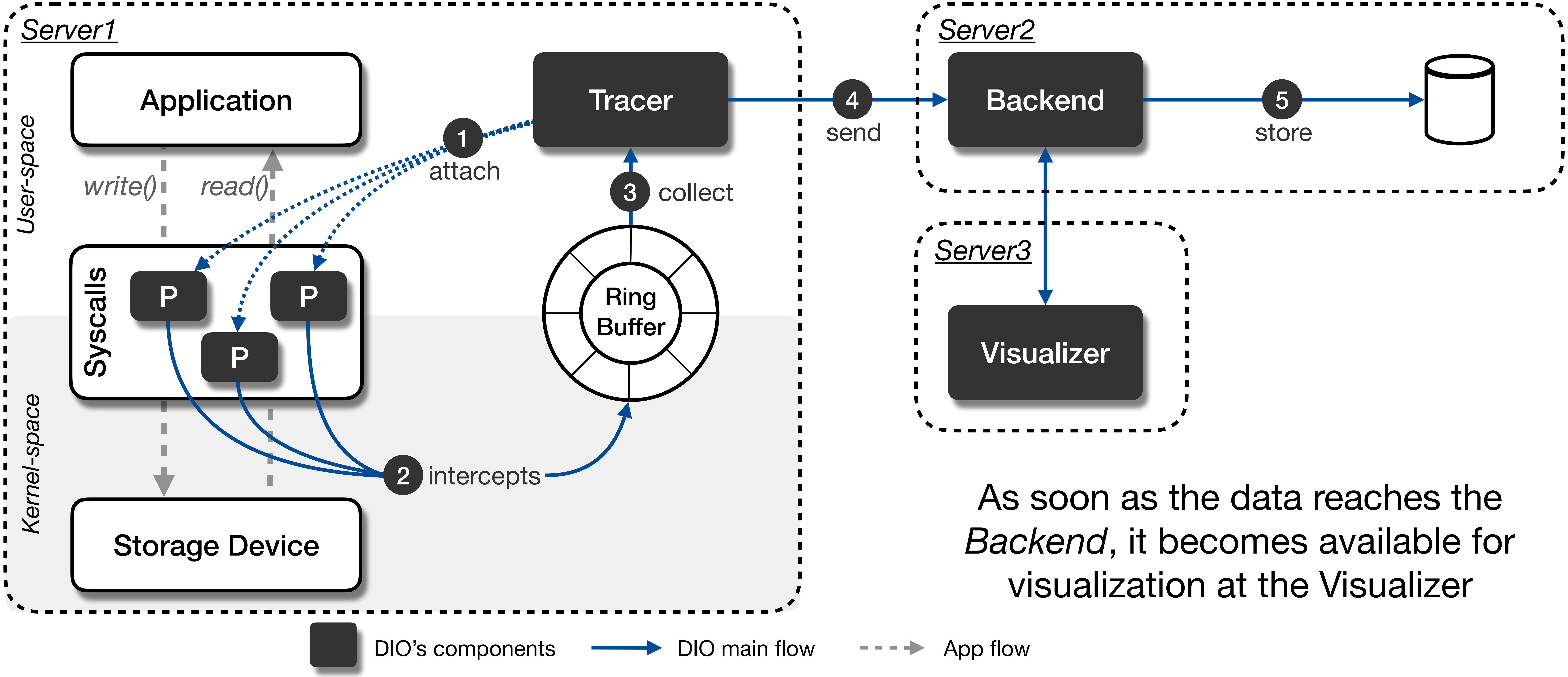

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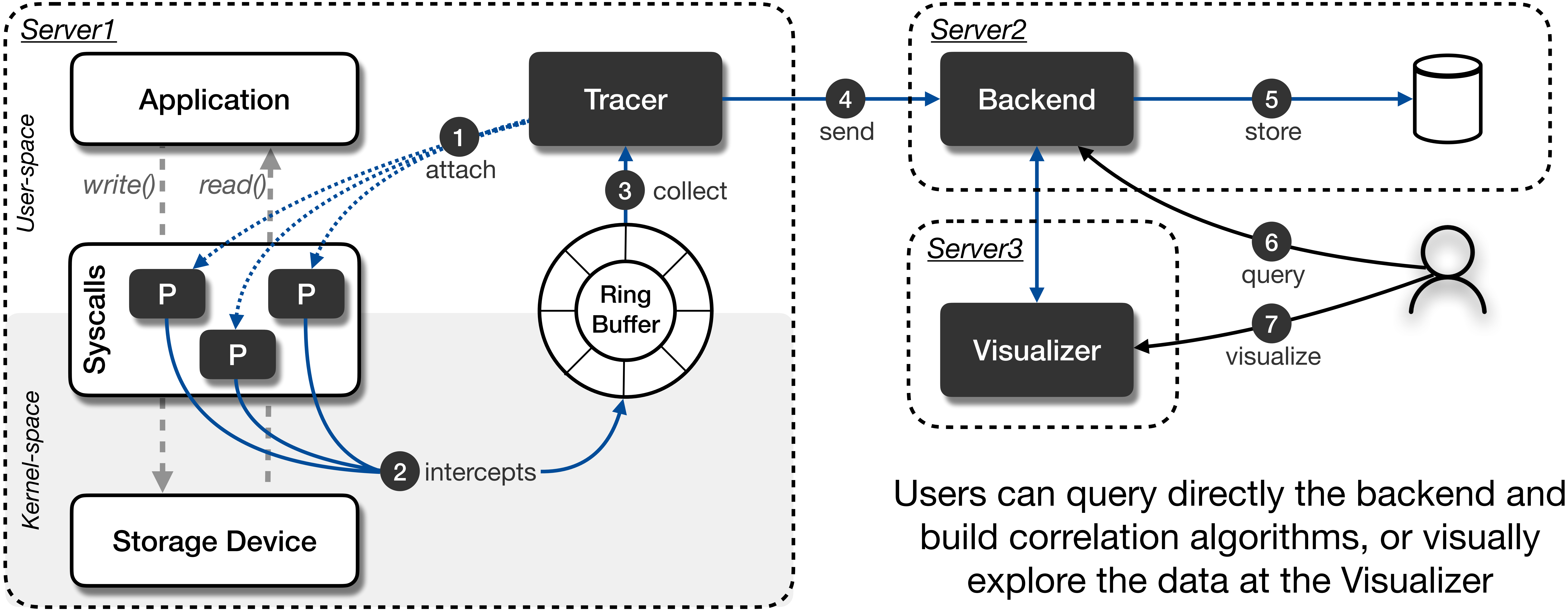


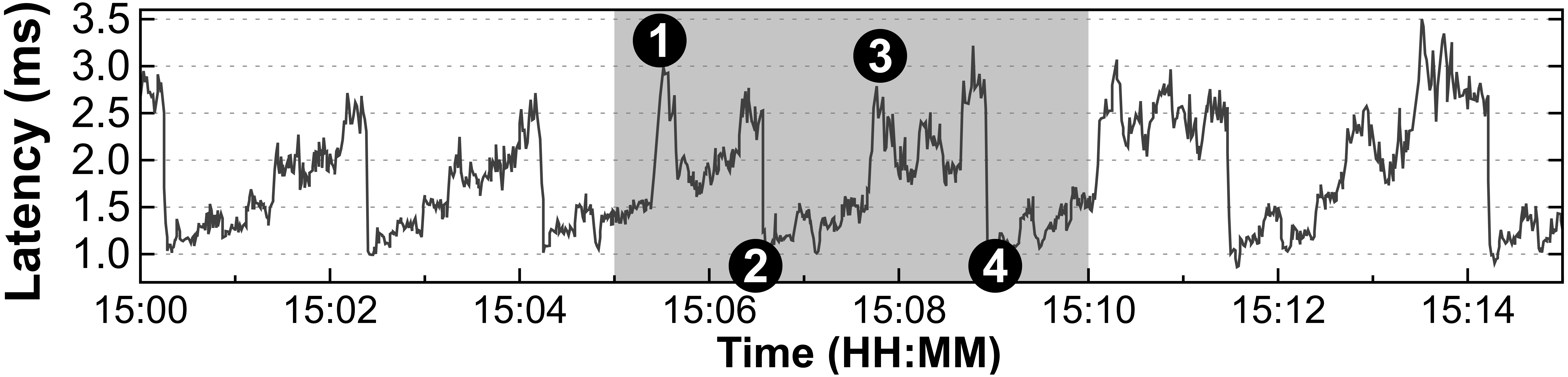
Users can query directly the backend and build correlation algorithms, or visually explore the data at the Visualizer

■ DIO's components —▶ DIO main flow - - -▶ App flow

DIO in Action

Finding the root cause of RocksDB’s performance anomalies

- **RocksDB:** An embedded key-value store
- **Problem:** RocksDB clients observe high tail latency (1 & 3)
  - Reproducible with db_bench benchmark



99th percentile latency for RocksDB client operations.

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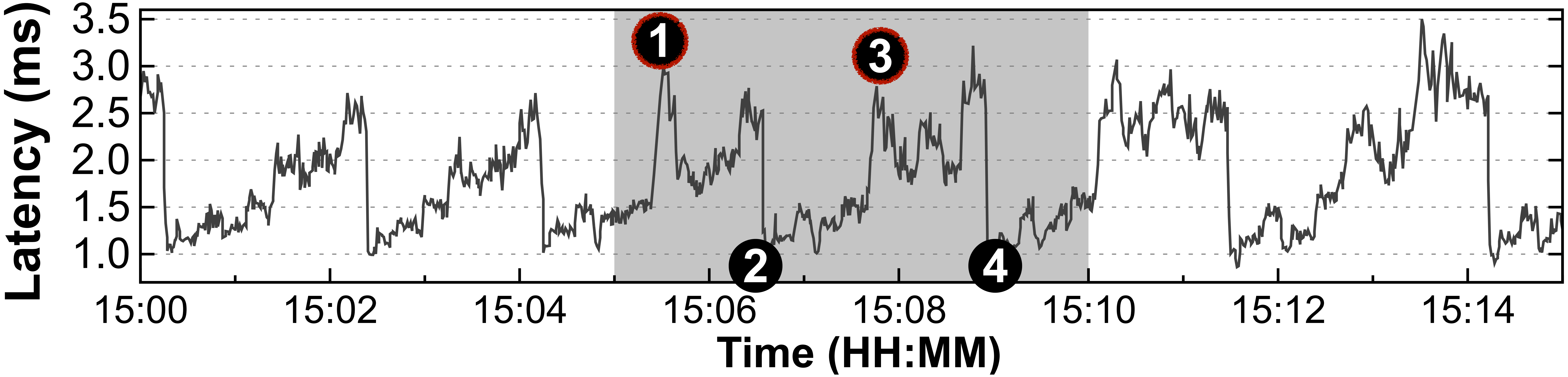

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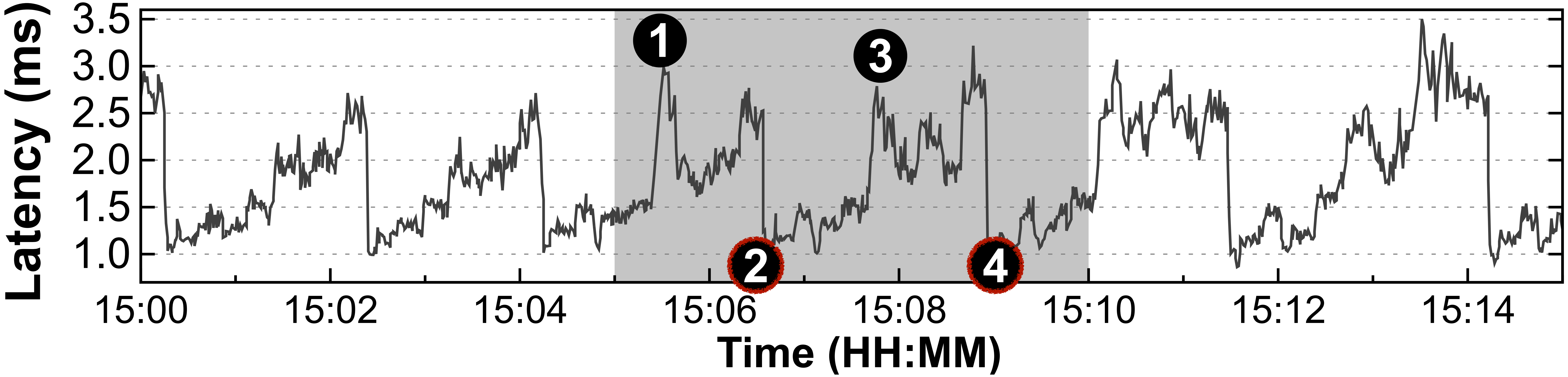

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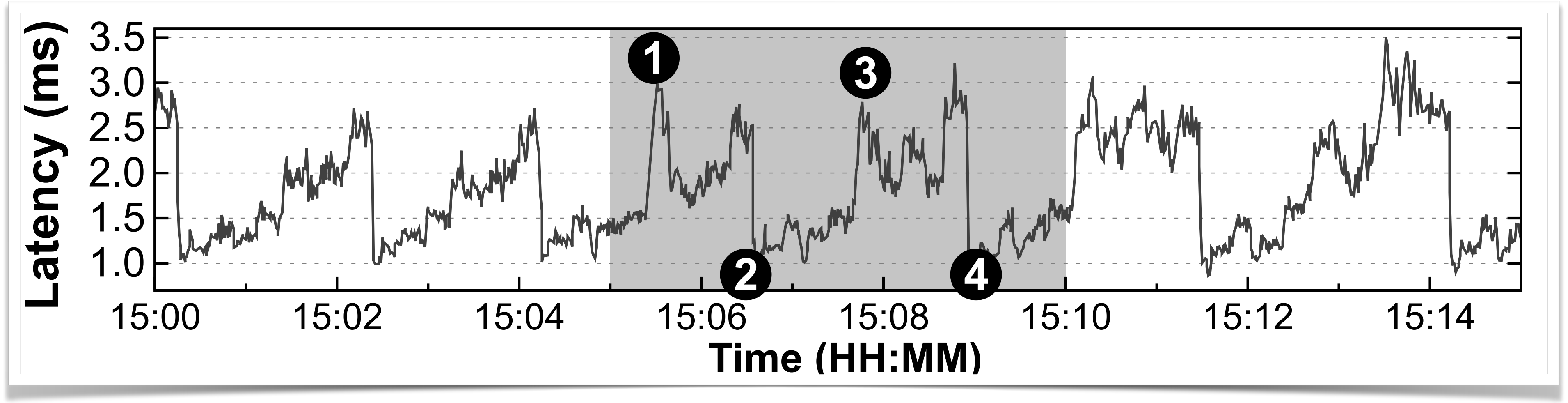
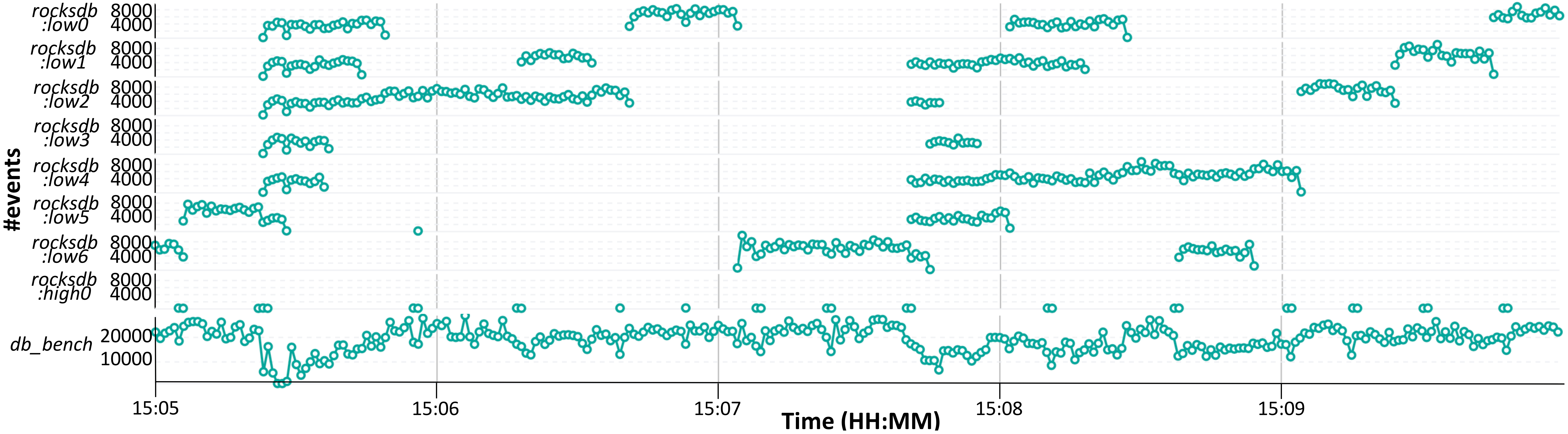
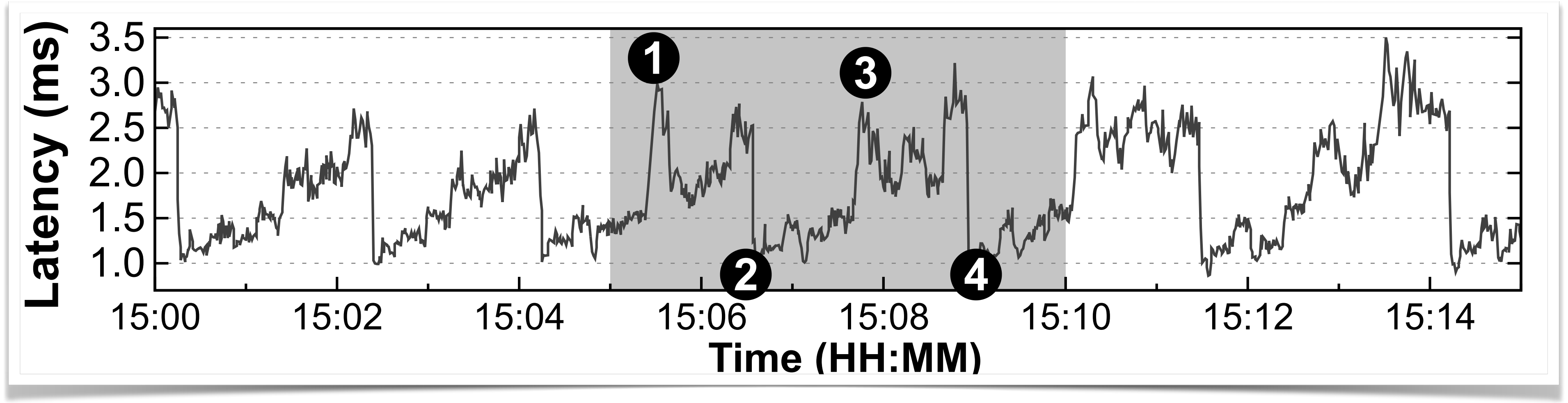




Syscalls issued by RocksDB over time, aggregated by thread name.

DIO in Action



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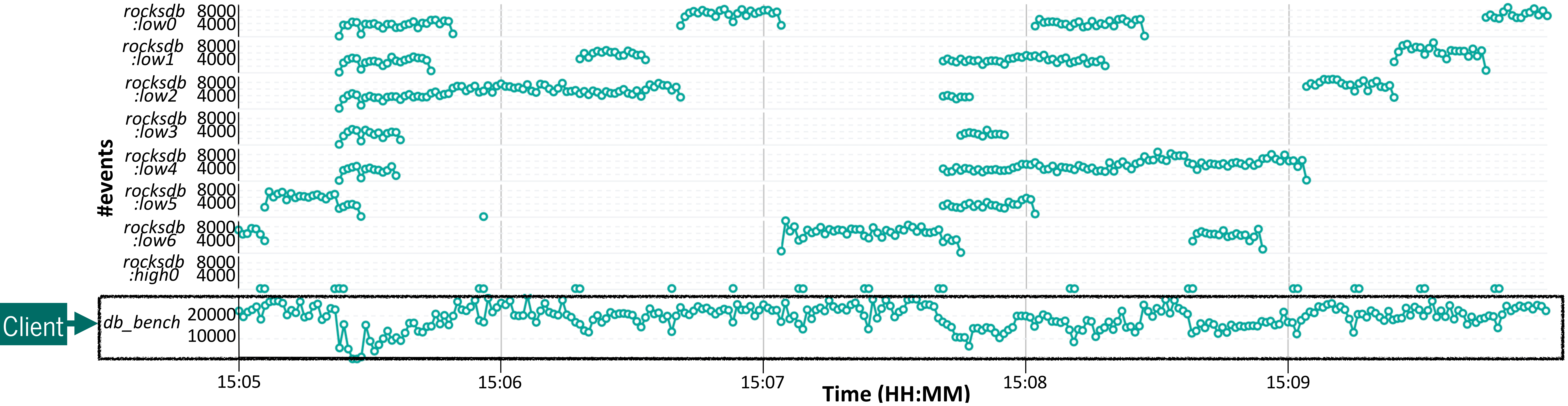

Syscalls issued by RocksDB over time, aggregated by thread name.

DIO in Action

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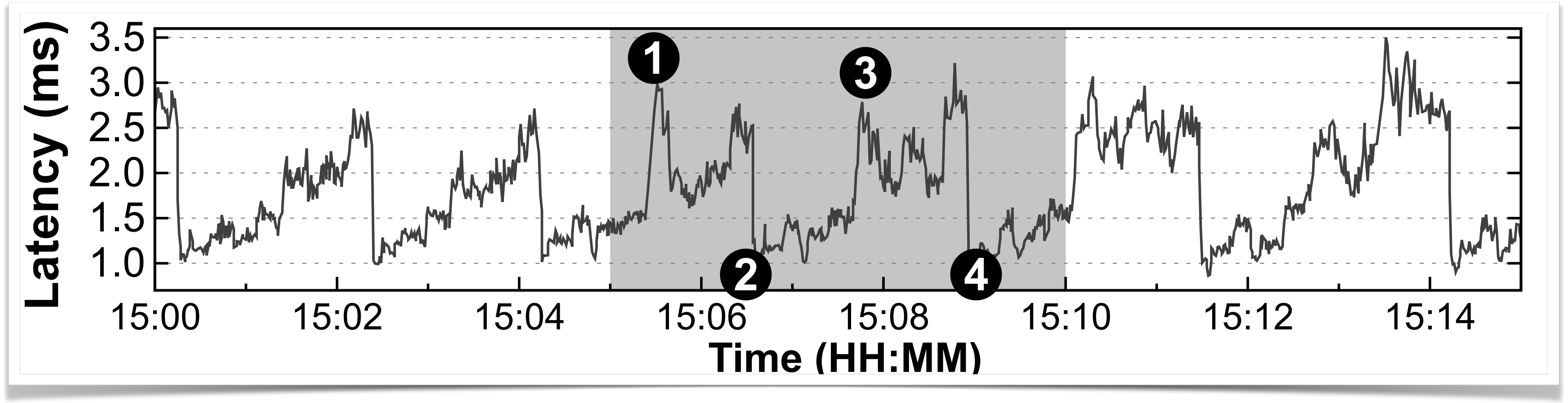

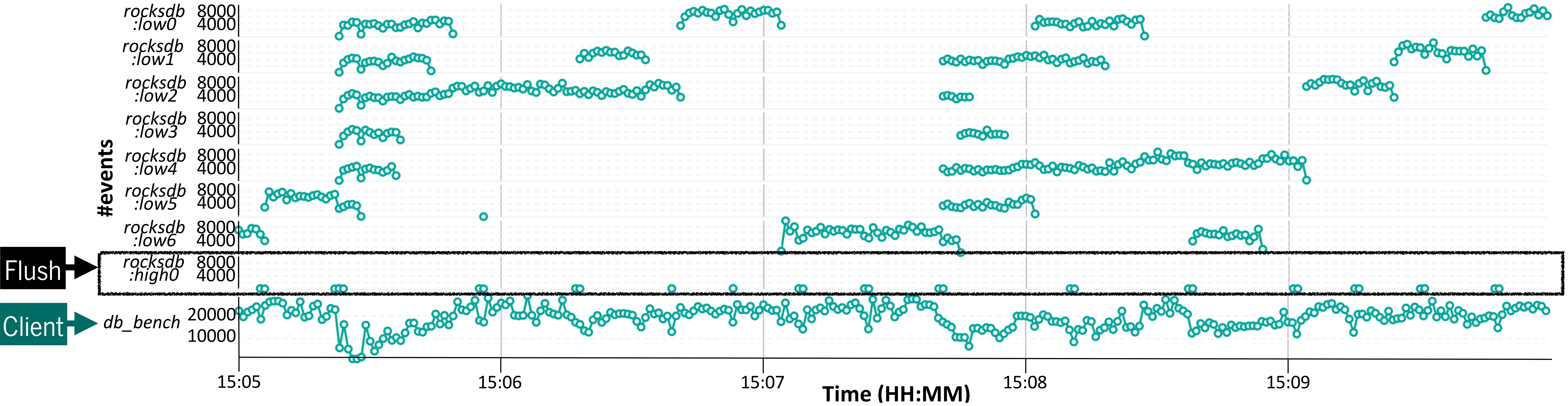

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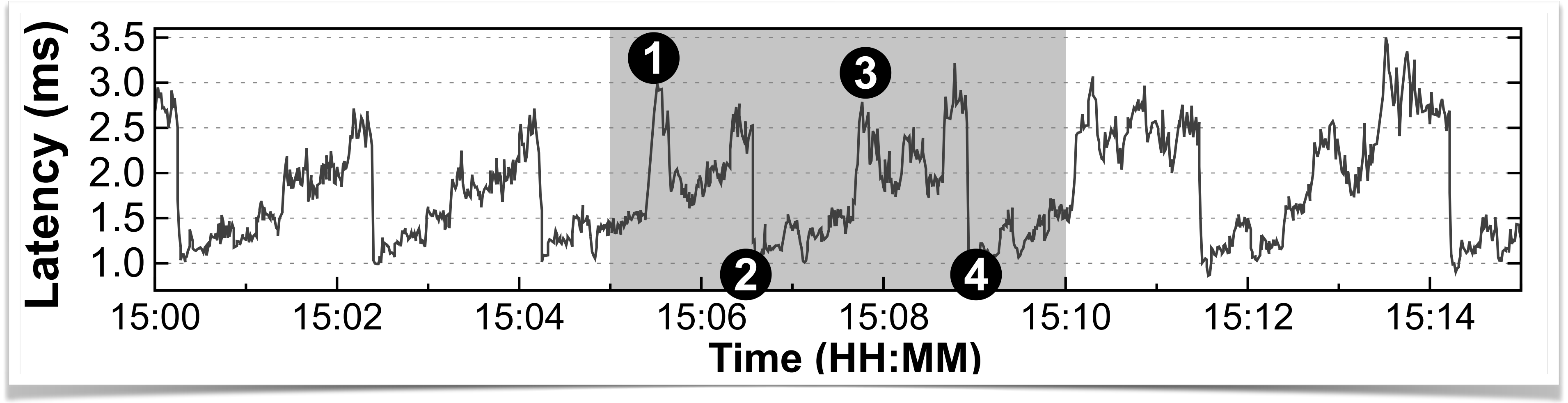

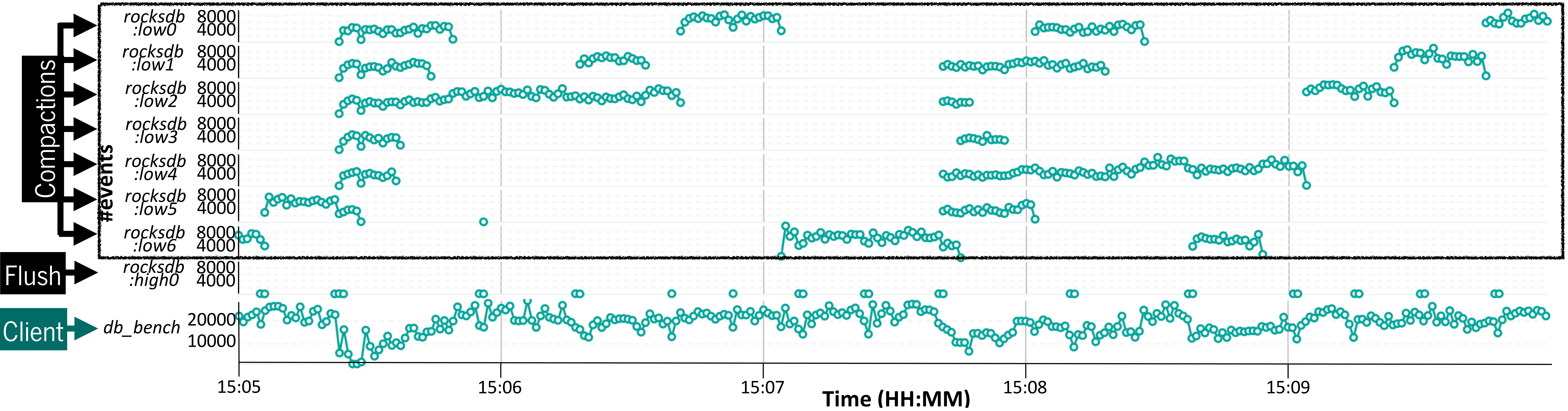

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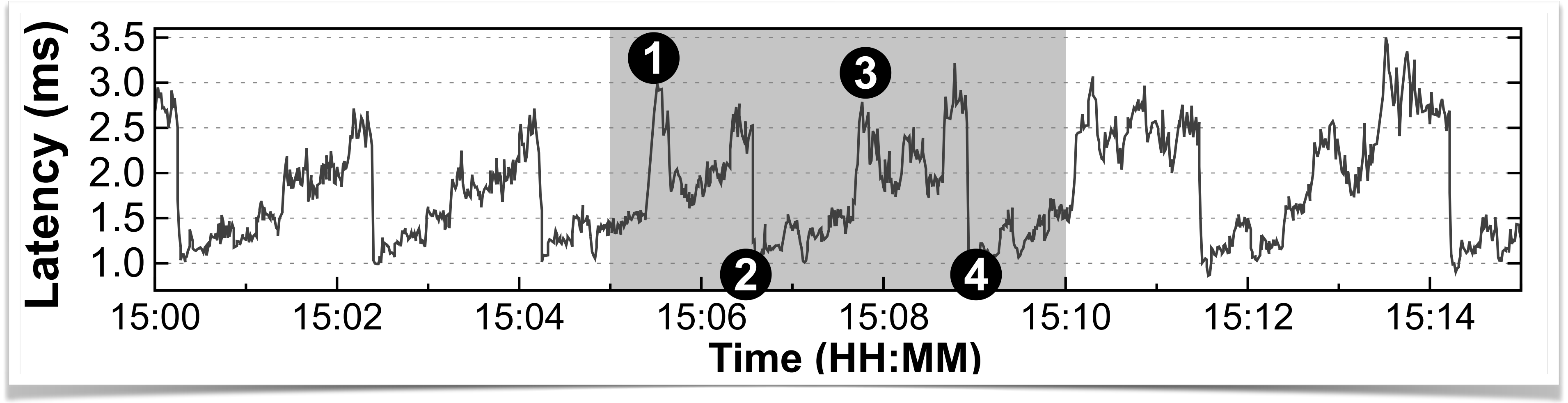

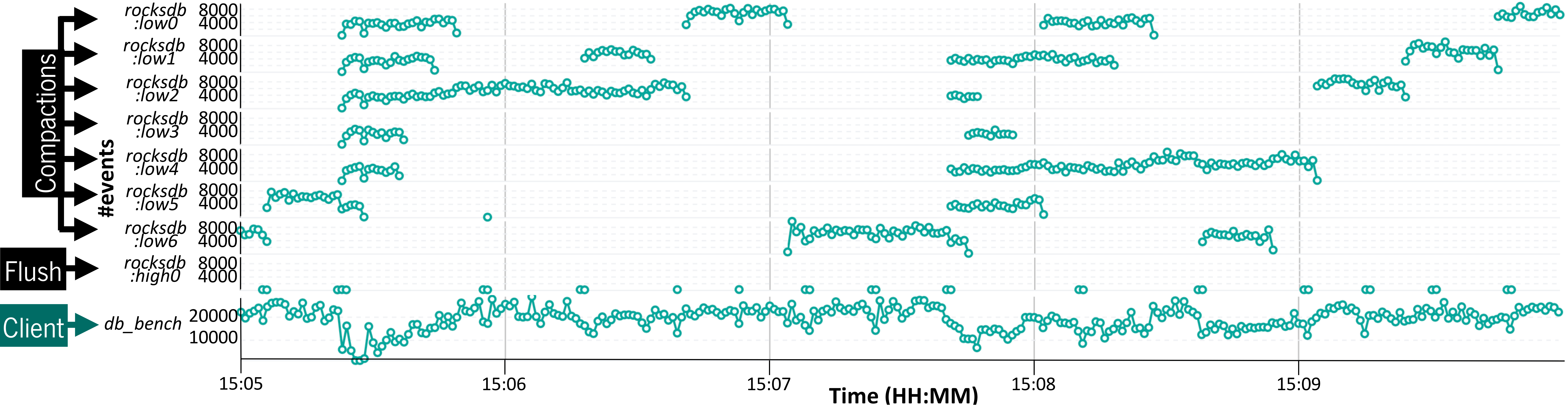

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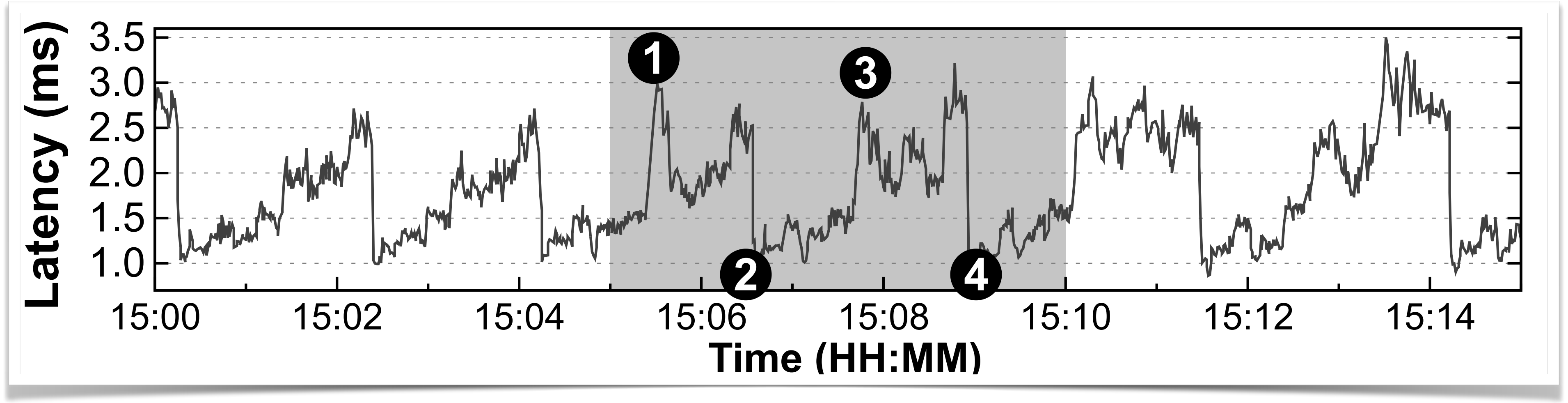

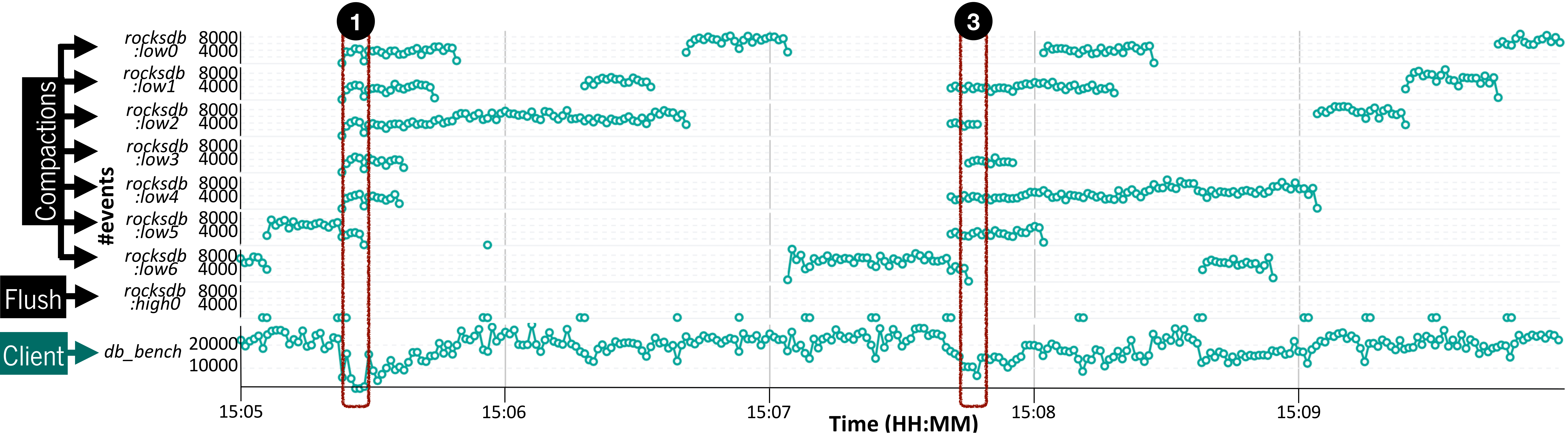

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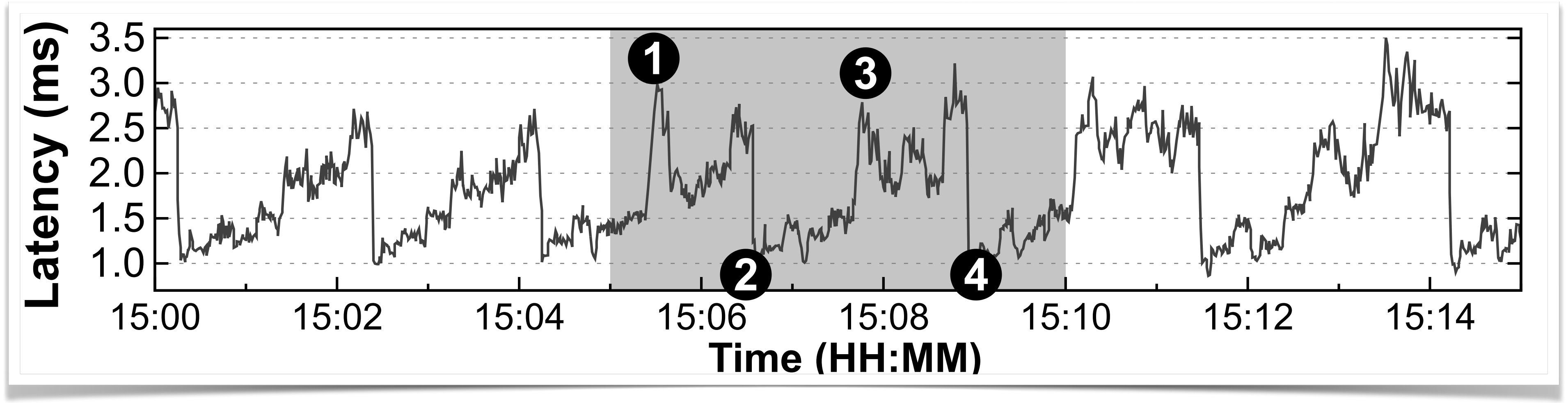
- (1&3) Multiple background threads perform I/O simultaneously, db_bench performance decreases



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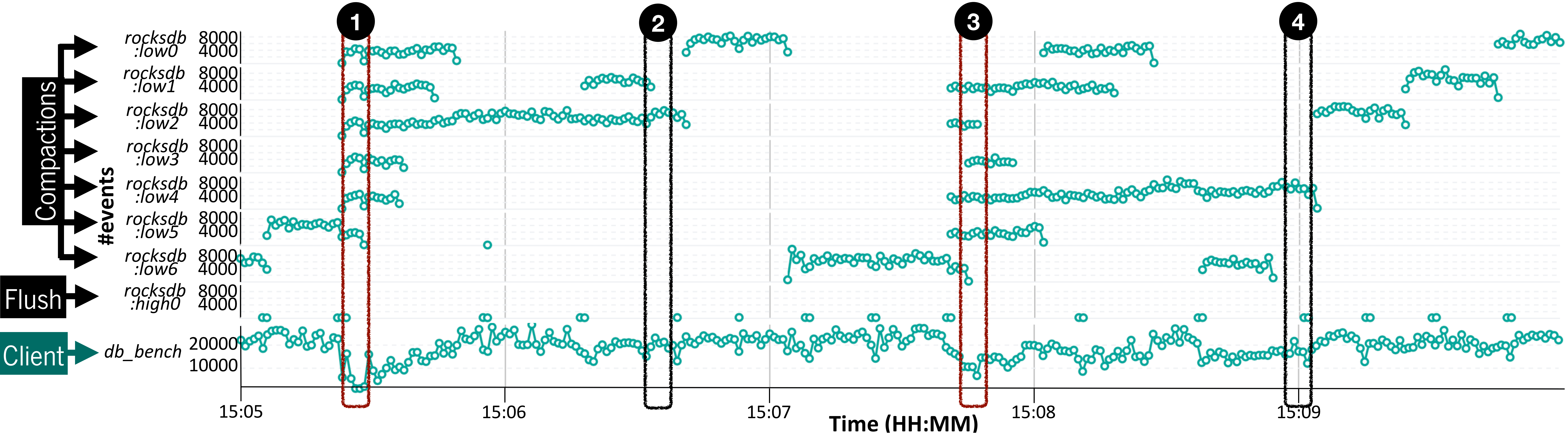

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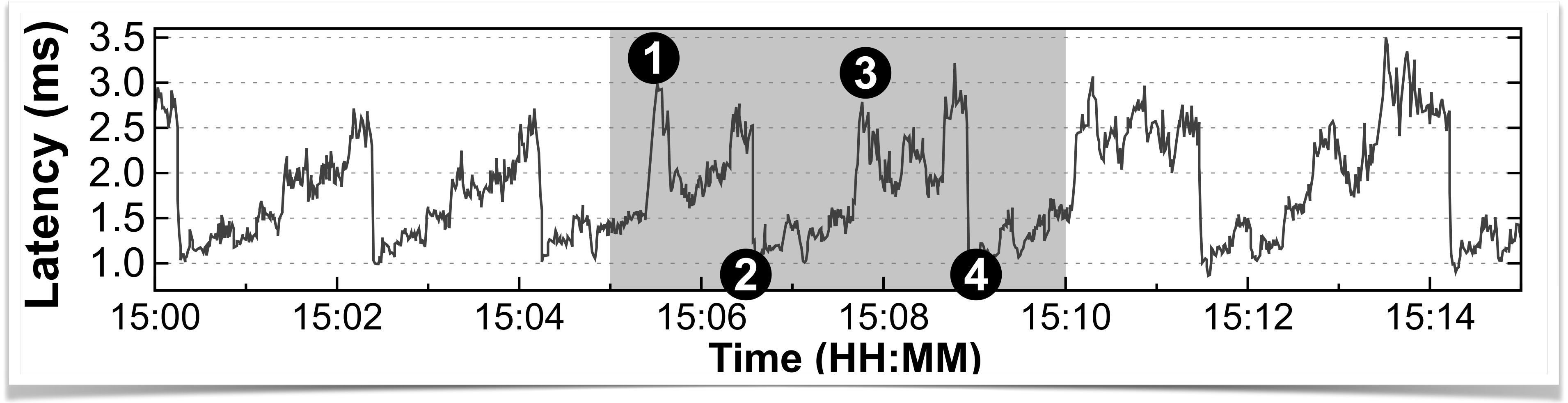
- (1&3) Multiple background threads perform I/O simultaneously, db_bench performance decreases
- (2&4) Few background threads perform I/O simultaneously, db_bench performance improves



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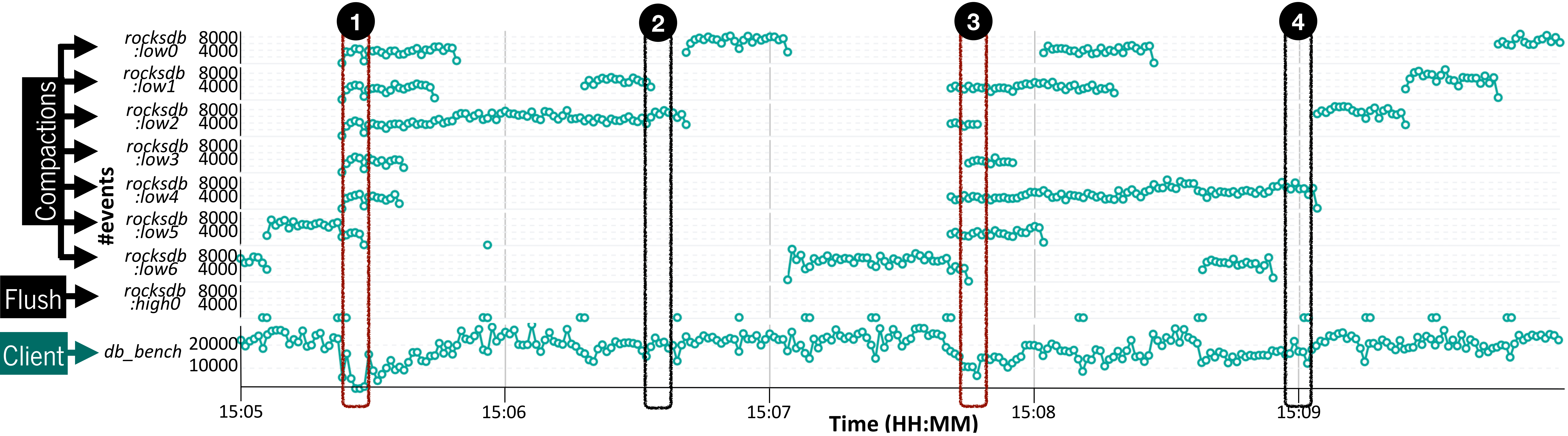

Syscalls issued by RocksDB over time, aggregated by thread name.

Root Cause: Interference between client writes, flushes and compactions

First observed in SILK (ATC'19) by instrumenting and manually inspecting more than 440K LoC

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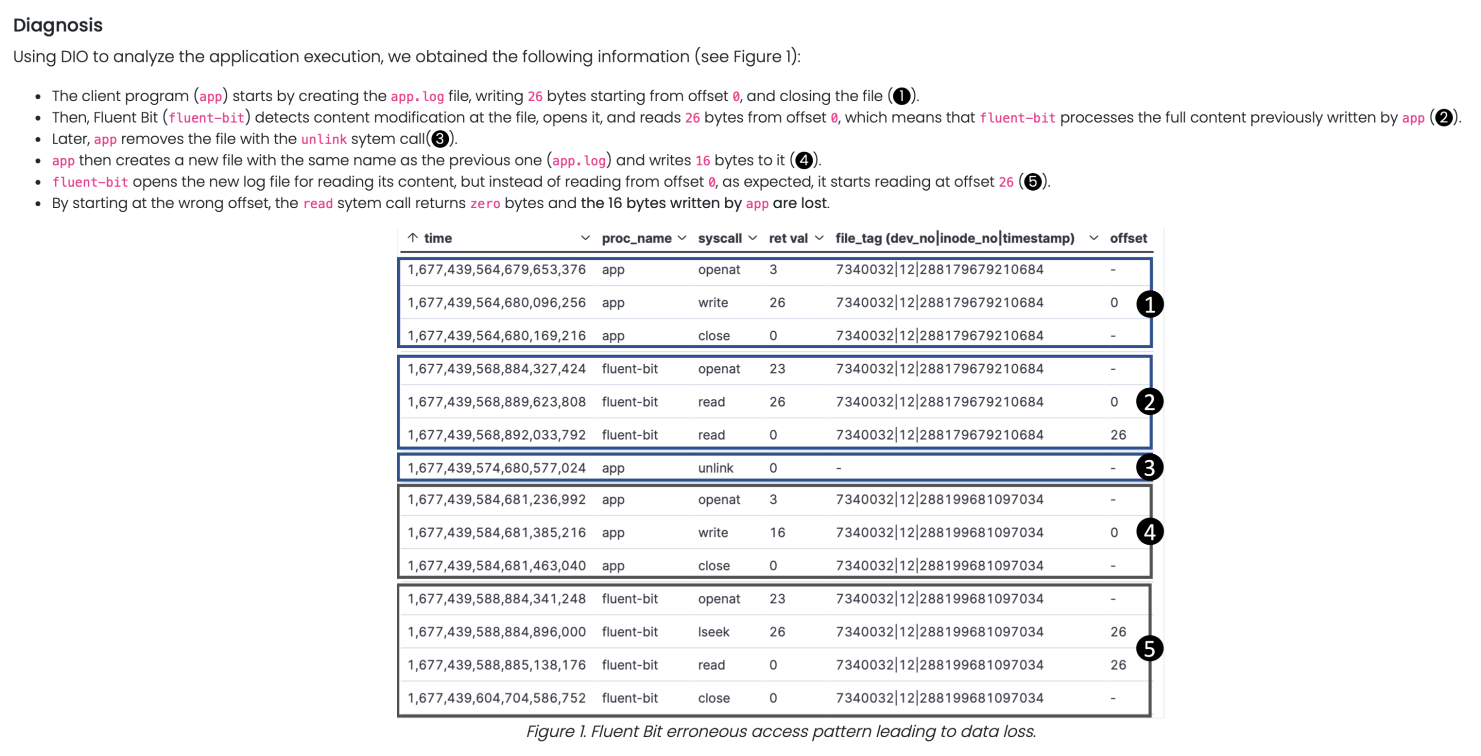
Fluent Bit

Identification of erroneous actions that lead to data loss



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1,677,439,564,680,096,256	app	write	26	7340032|12|288179679210684	0	❶
1,677,439,564,680,169,216	app	close	0	7340032|12|288179679210684	-	
1,677,439,568,884,327,424	fluent-bit	openat	23	7340032|12|288179679210684	-	
1,677,439,568,889,623,808	fluent-bit	read	26	7340032|12|288179679210684	0	❷
1,677,439,568,892,033,792	fluent-bit	read	0	7340032|12|288179679210684	26	
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1,677,439,584,681,236,992	app	openat	3	7340032|12|288199681097034	-	
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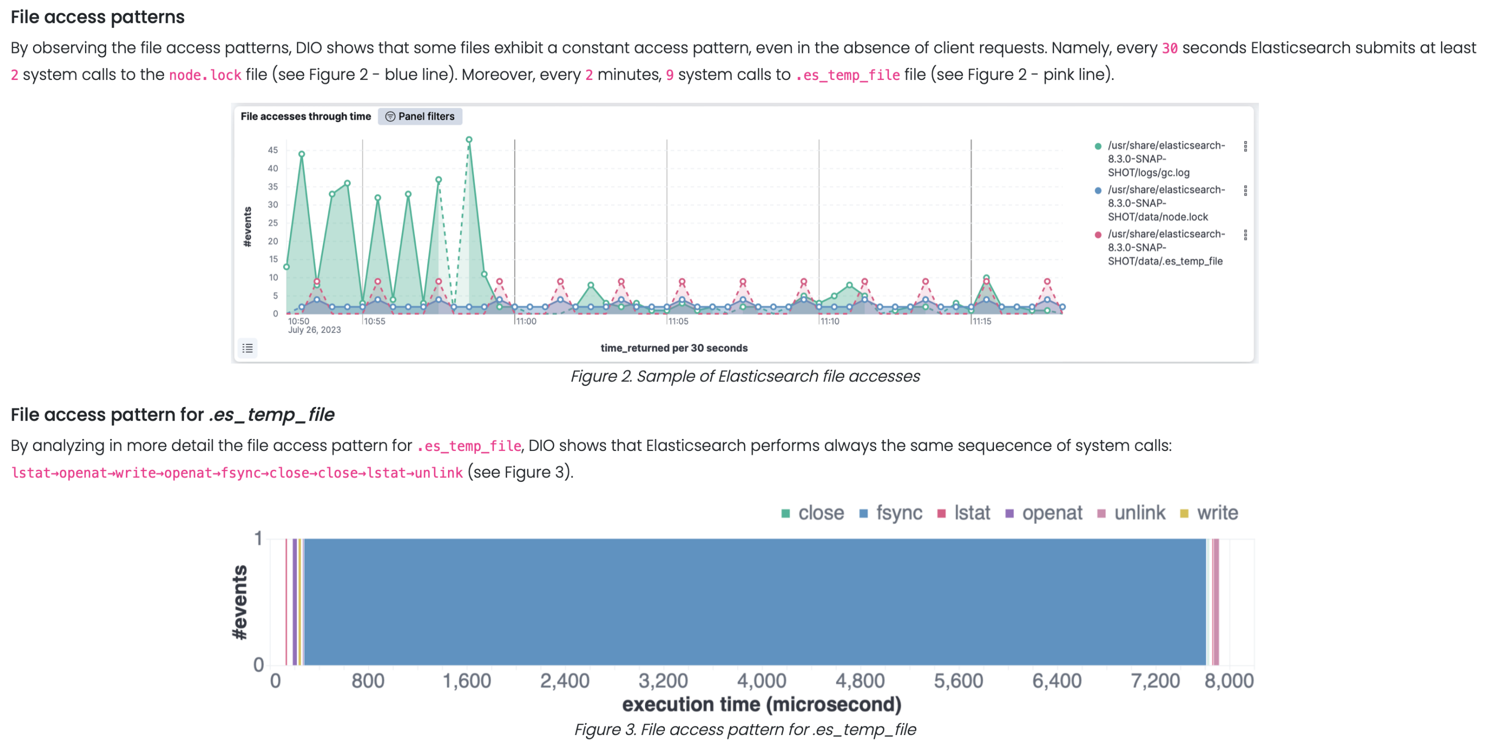
Elasticsearch

Top-down exploration and I/O diagnosis



File access patterns

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Panel filters
#events
0
5
10
15
20
25
30
35
40
45
10:50
July 26, 2023
10:55
11:00
11:05
11:10
11:15
time_returned per 30 seconds
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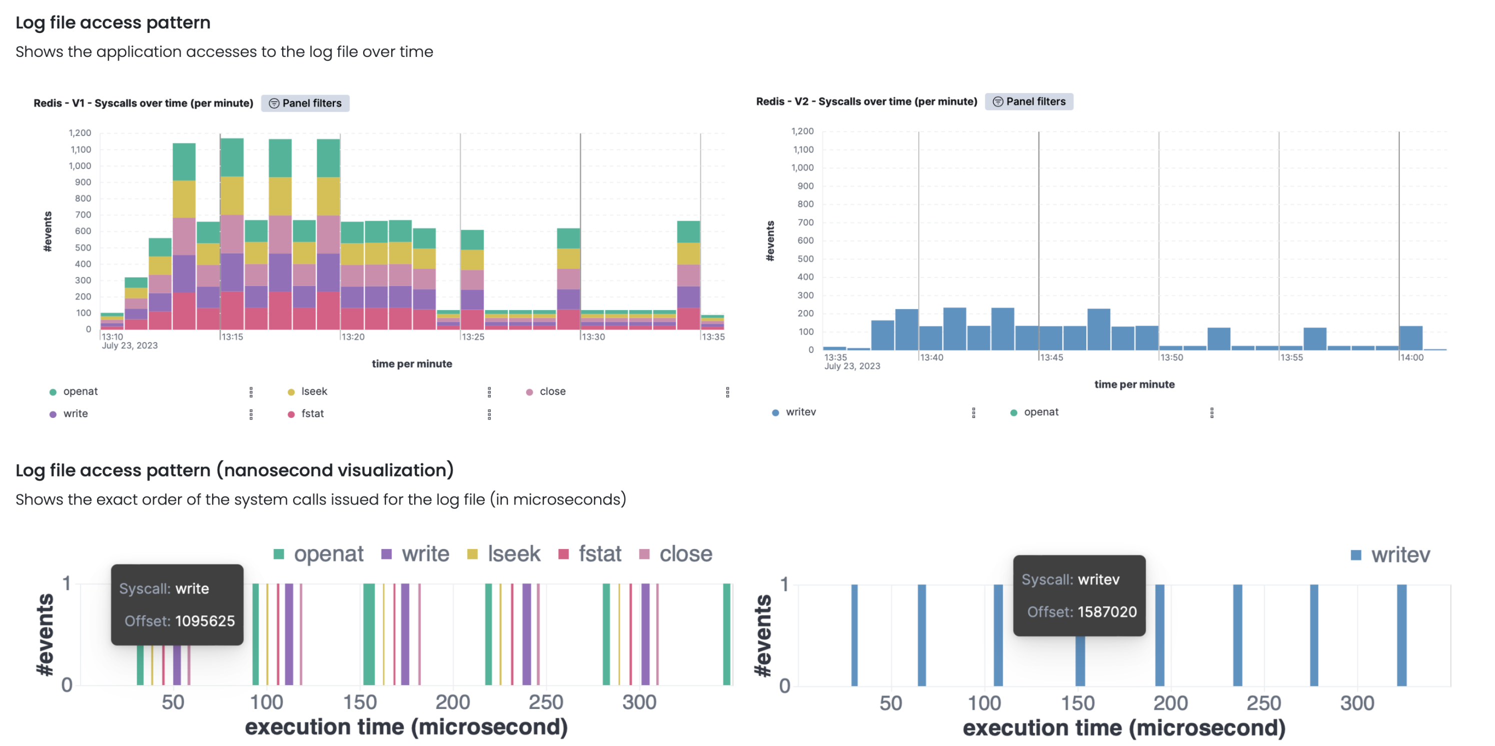
Figure 3. File access pattern for .es_temp_file

Redis

Debugging and validation of inefficient I/O patterns



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Shows the application accesses to the log file over time

Log file access pattern (nanosecond visualization)

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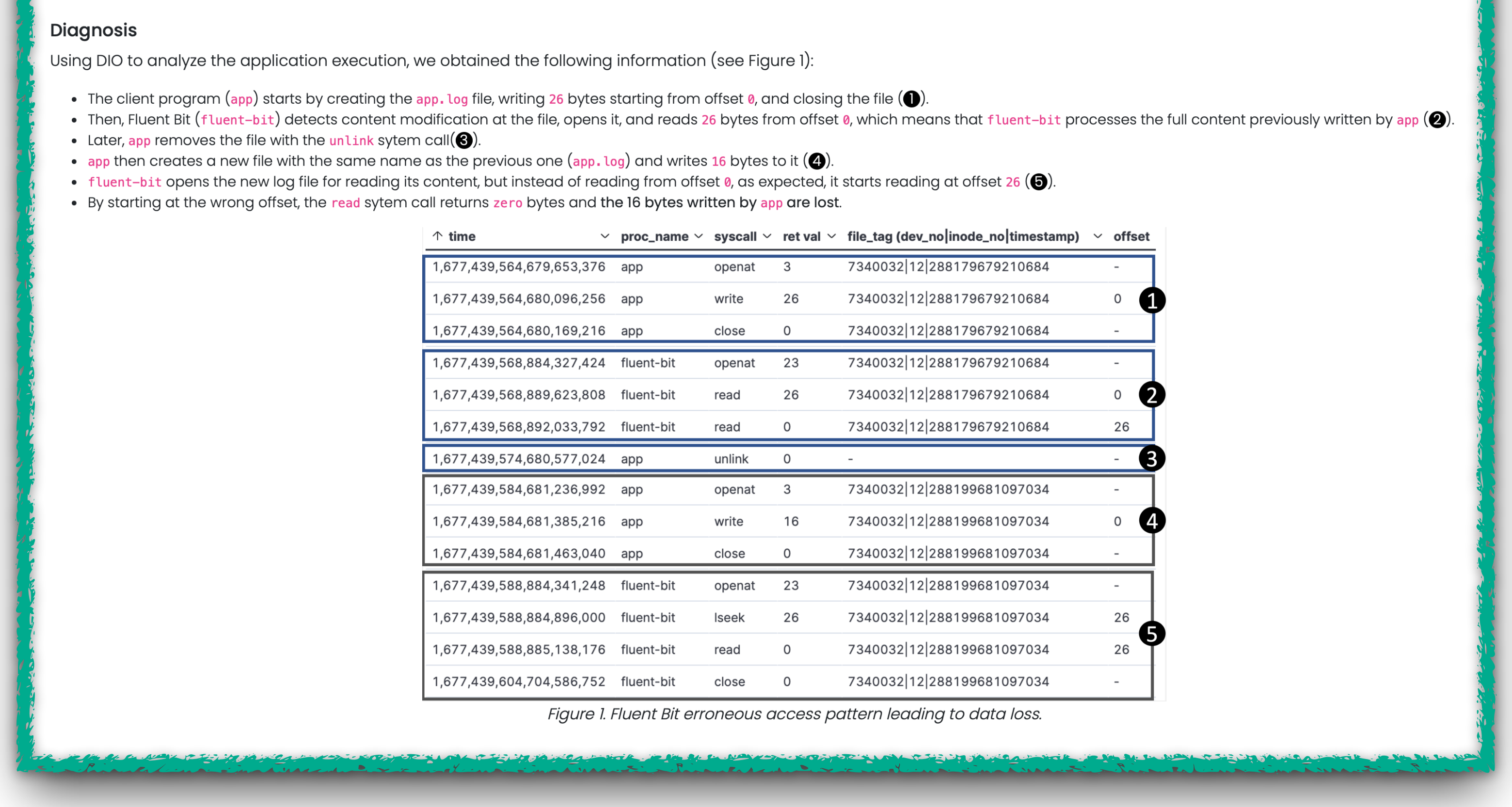

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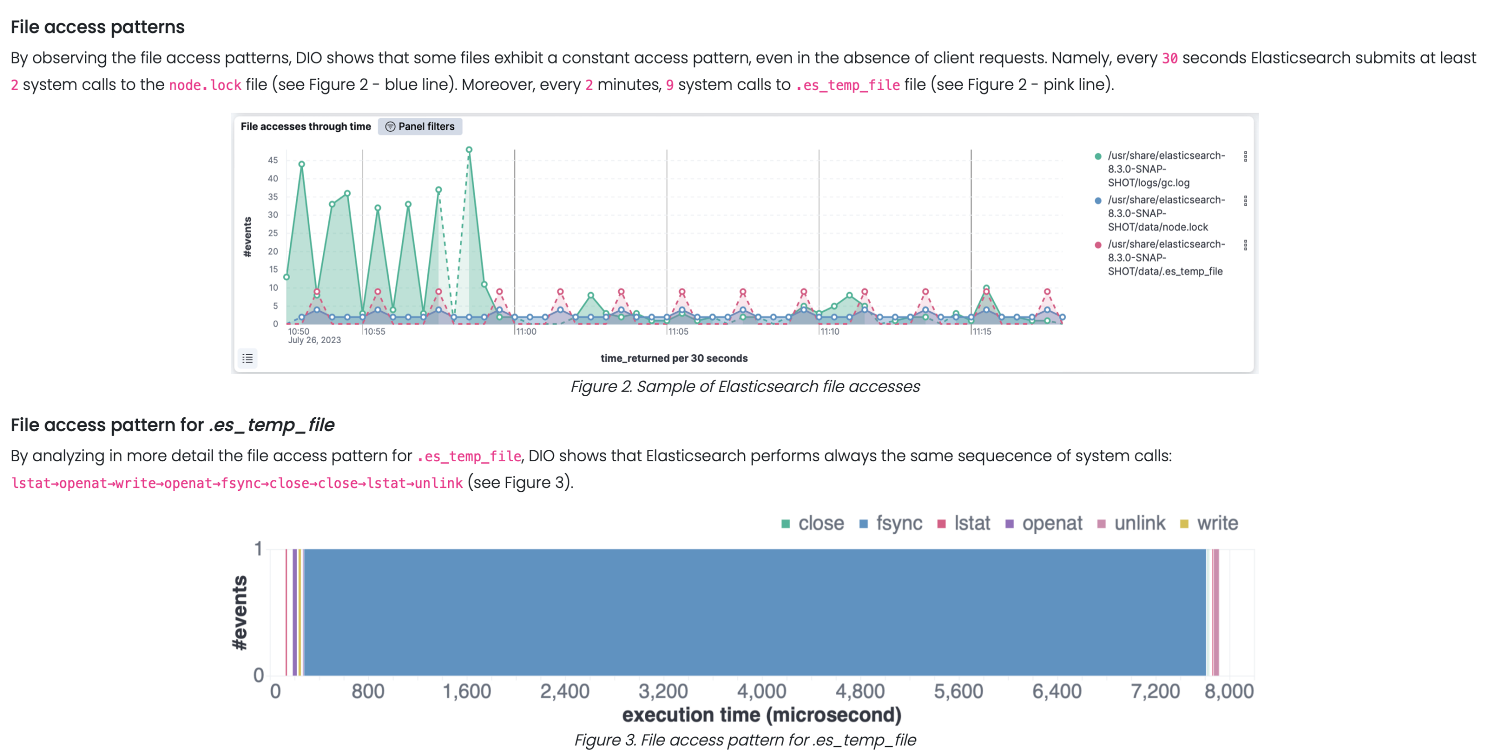

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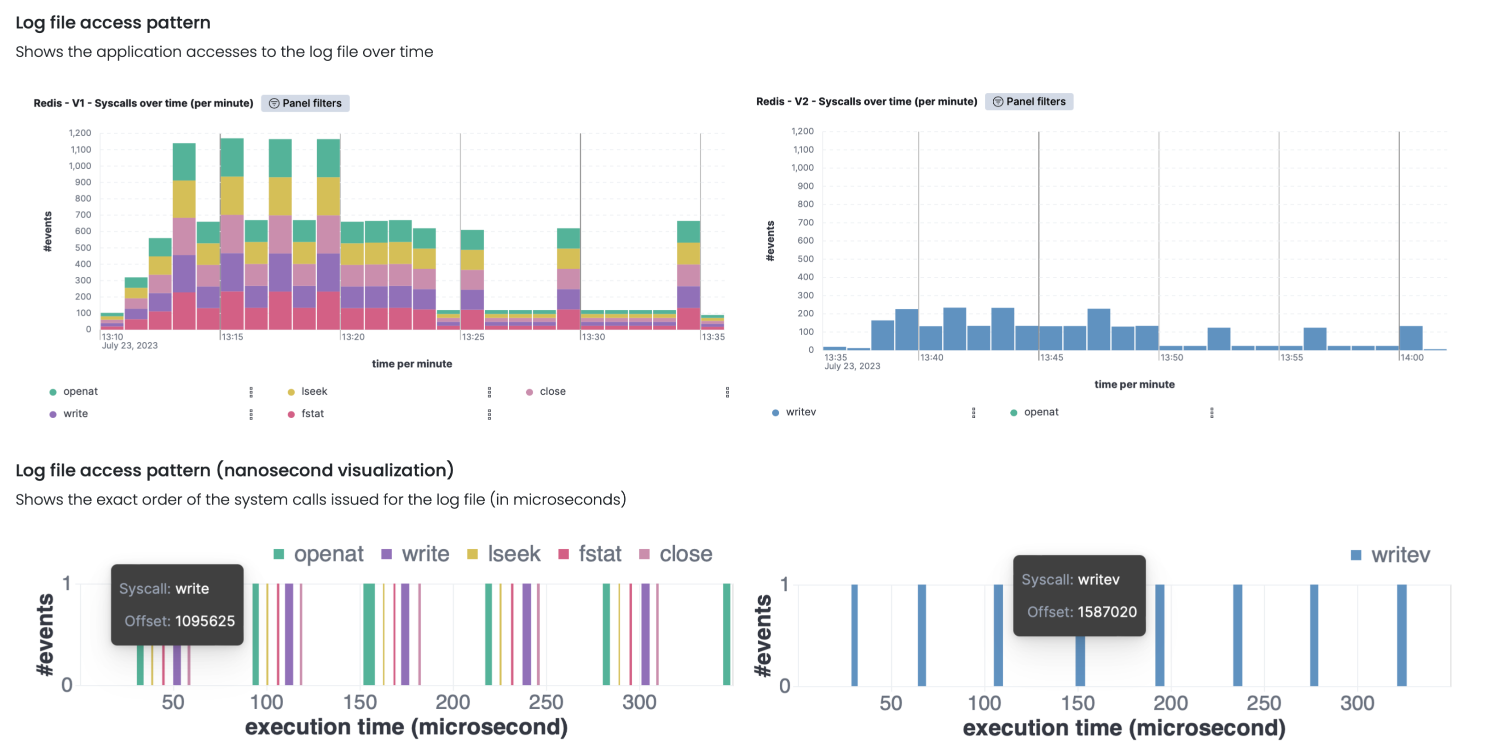

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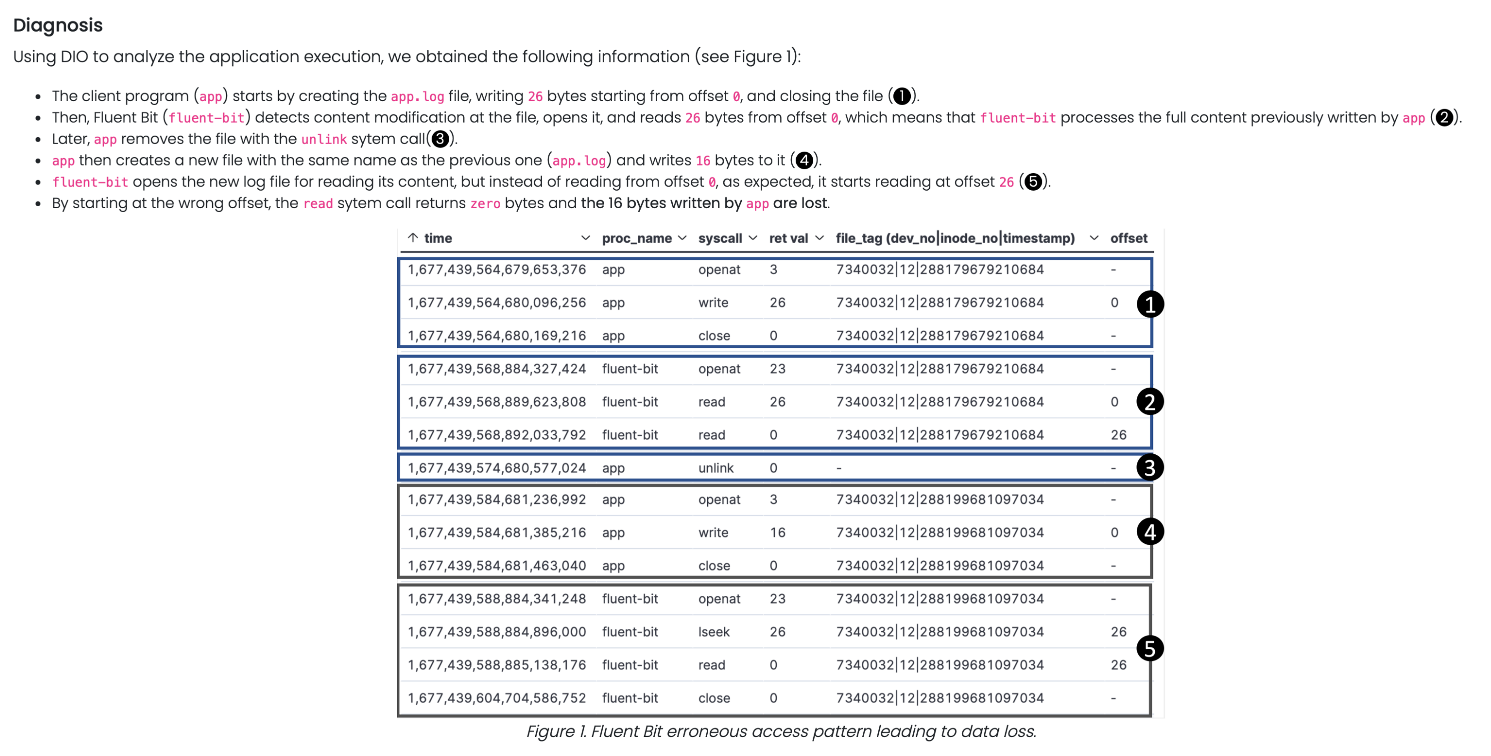

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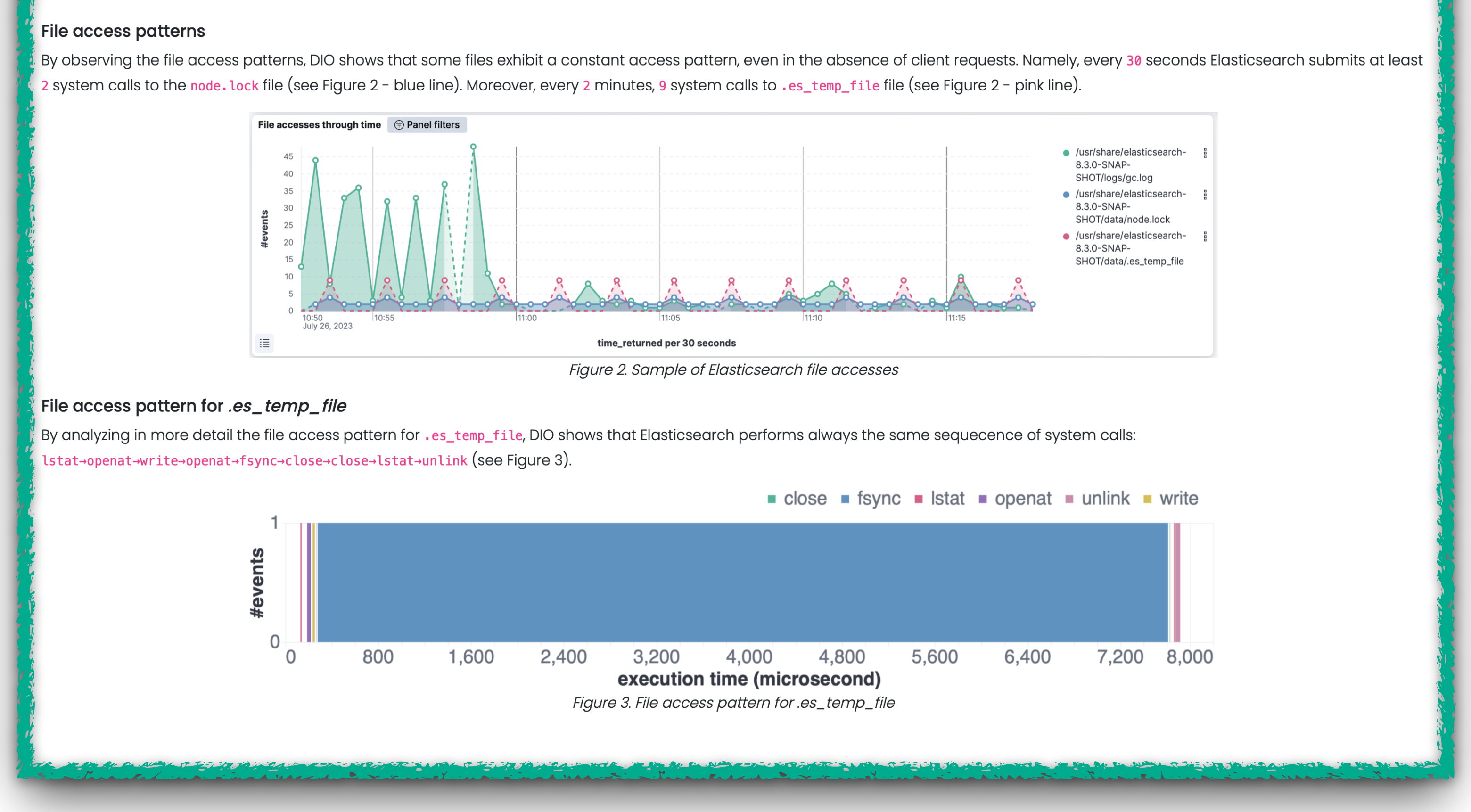

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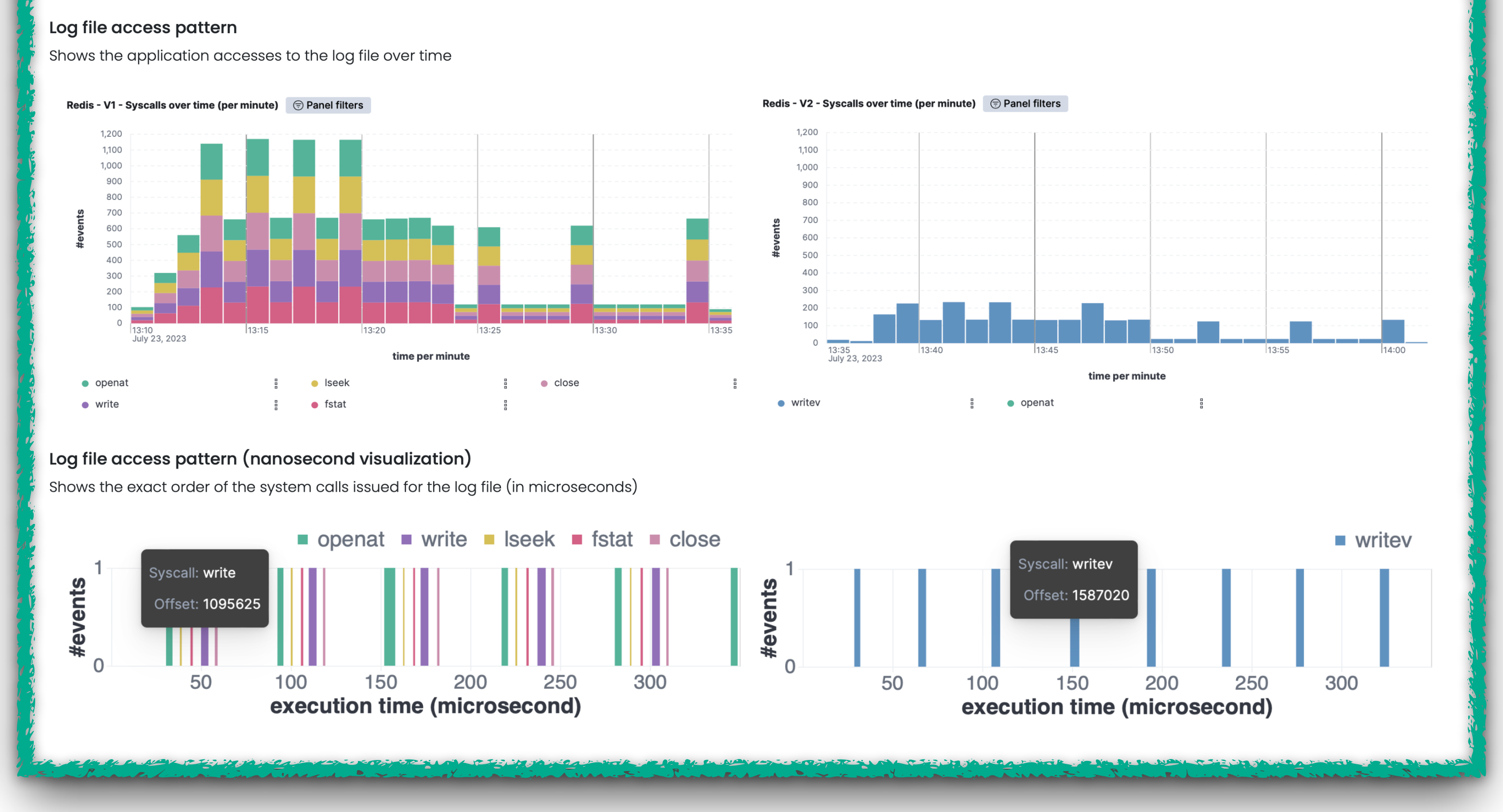

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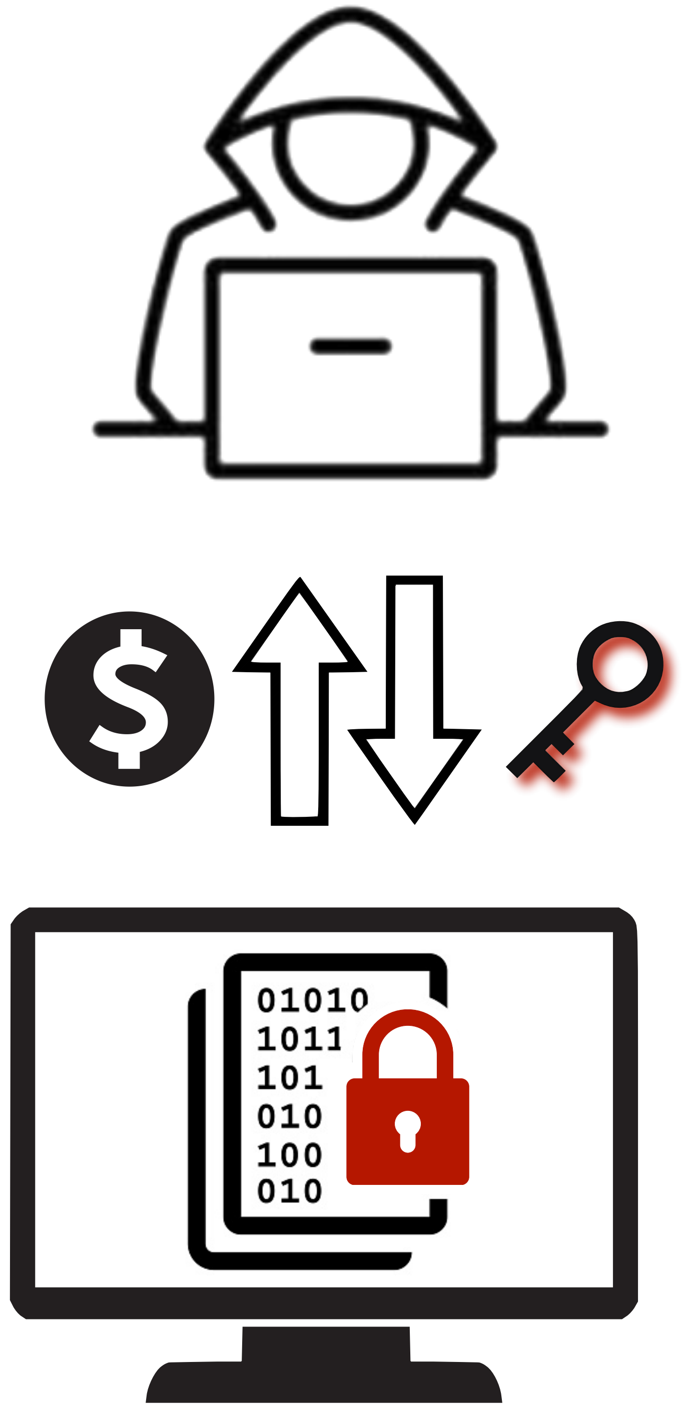
Custom and Improved Analysis

CRIBA, a tool for diagnosing the I/O behavior of Linux cryptographic ransomware

- Supports the collection of 13 network-related system calls and system metrics
- Enhances the analysis process with 6 correlation algorithms and 8 dashboards tailored for ransomware characterization

Cryptographic Ransomware

- **Malicious software** that **encrypts** victim’s data and demands a **ransom**
- New ransomware families are constantly appearing
- CRIBA allows the observation of **characteristic** ransomware behavior:
  - Traverses all victims’ directories
  - Rewrites victims’ files with encrypted data
  - Adds a new file extension to encrypted files
  - Leaves ransom notes to inform the victim
  - Has high CPU consumption due to encryption algorithms



CRIBA in Action

- Study with 5 different Linux cryptographic ransomware families

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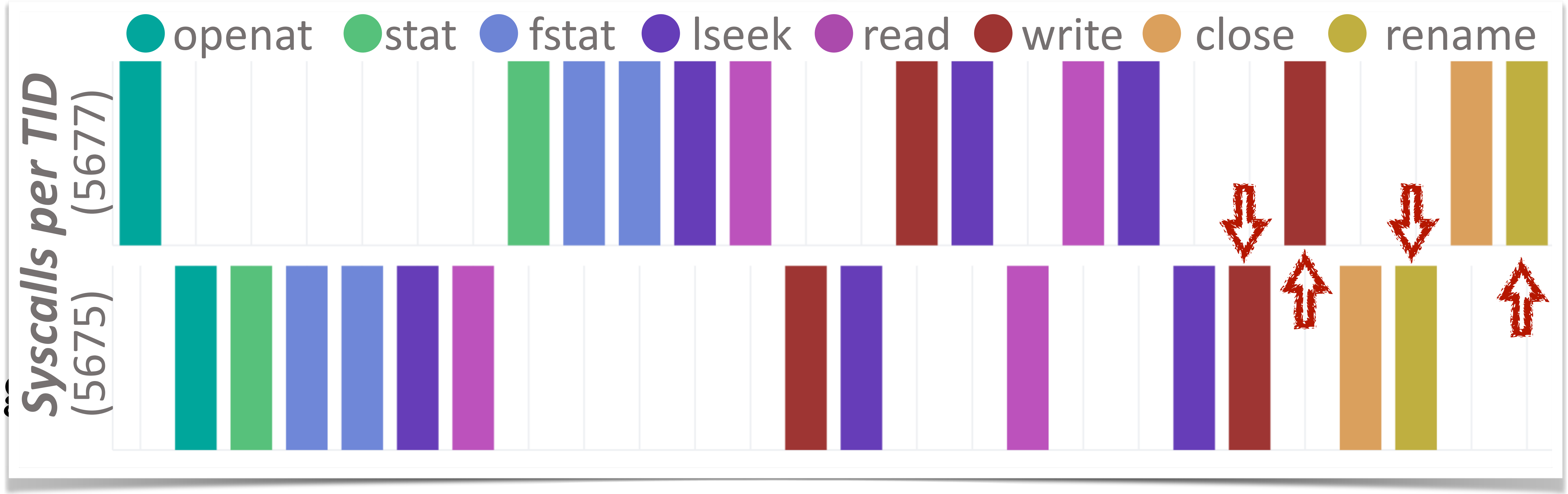

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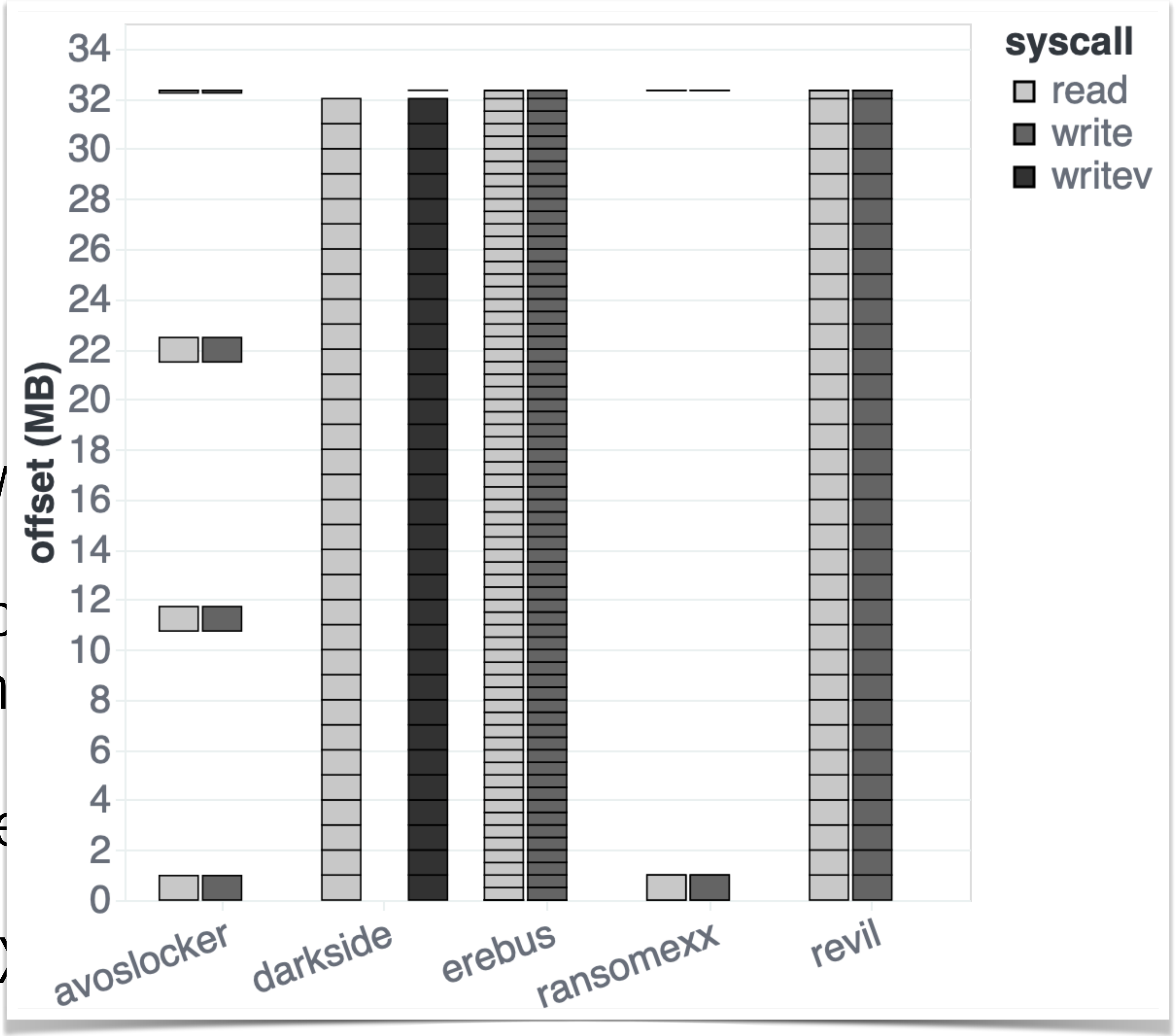
  - Some families process only **partial content** of files or target **specific file extensions**



CRIBA Summary

- CRIBA highlights **DIO’s usefulness** by extending it with tailored analysis and visualization
- Our study shows that **different features** must be considered for a **clear understanding** of ransomware’s **intrinsic** behavior
- This knowledge is key for improving detection tools for Linux cryptographic ransomware

Conclusion

- **CaT**, a framework for diagnosing storage and network I/O requests of **distributed systems**
  - Follows a content-aware approach that allows observing how data flows across components
  - Useful for uncovering data corruption and adulteration issues

- **DIO**, a generic tool for diagnosing **data-centric applications**’ storage I/O
  - Provides the flexibility to narrow or broaden the collection, analysis and visualization of I/O behaviors
  - Useful for debugging, validating and exploring both known and unknown storage patterns

- **CRIBA**, a practical tool for characterizing the I/O behavior of **cryptographic ransomware**
  - Automates the analysis and visualization of specific ransomware behaviors
  - Useful for better understand ransomware attacks and enhance detection tools

Publications

Core Publications

- **Tânia Esteves**, Francisco Neves, Rui Oliveira and João Paulo. **"CaT: Content-aware Tracing and Analysis of Distributed Systems"**. In *22nd International Middleware Conference*, 2021.
- **Tânia Esteves**, Ricardo Macedo, Rui Oliveira and João Paulo. **"Diagnosing Applications' I/O Behavior through System Call Observability"**. In *53rd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshops*, 2023.
- **Tânia Esteves**, Bruno Pereira, Rui Pedro Oliveira, João Marco and João Paulo. **"CRIBA: A Tool for Comprehensive Analysis of Cryptographic Ransomware's I/O Behavior"**. In *42nd Symposium on Reliable Distributed Systems*, 2023.
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