Shadow Filesystems: Recovering from Filesystem Runtime Errors via Robust Alternative Execution

Jing Liu, Xiangpeng Hao

Andrea Arpaci-Dusseau, Remzi Arpaci-Dusseau, Tej Chajed

University of Wisconsin–Madison

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Existing Filesystems:
Excels at Performance OR Correctness

Performance	Correctness
Caches, concurrency, parallelism, etc
Kernel filesystems (e.g., ext4, btrfs)
DevFS (FAST ’18)
LineFS (SOSP ’21)
uFS (SOSP ’21)

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DevFS (FAST '18)	Cogent (ASPLOS '16)
LineFS (SOSP '21)	Yggdrasil (OSDI '16)
uFS (SOSP '21)	AtomFS (SOSP '19)
	DaisyNFS (OSDI '22)
Correctness is difficult	**Performance is difficult**

Can we build a file system that has both high performance AND correctness

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use two filesystems

Idea: Two Filesystems to Achieve Both

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uFS (SOSP '21) → Performance AND Correctness ← uFS-Shadow

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Robust Alternative Execution

RAE: Robust Alternative Execution

Two filesystems

- A base filesystem (common path)
  - High performance
- A shadow filesystem (alternative path)
  - Correctness
  - Handles the workload that triggers a bug in the base

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  - Handles the workload that triggers a bug in the base

Can even survive deterministic bugs in the base

Outline

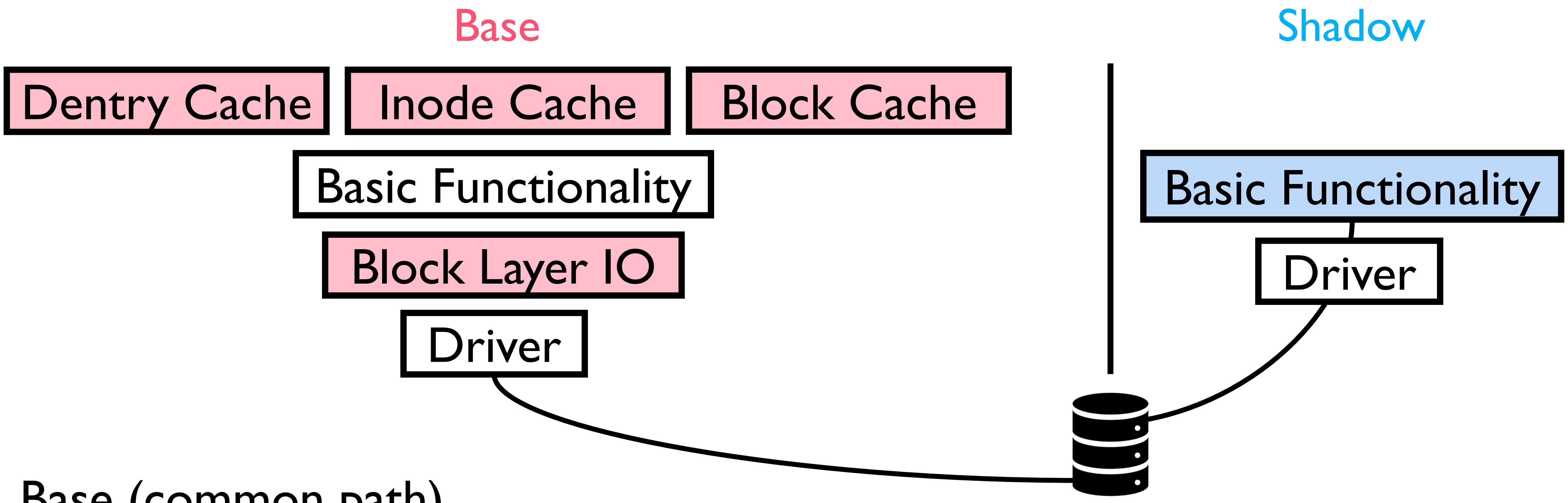
Introduction

Robust Alternative Execution (RAE)

Prototype and Progress Status

Future Challenges

RAE: The Base and Shadow Filesystems



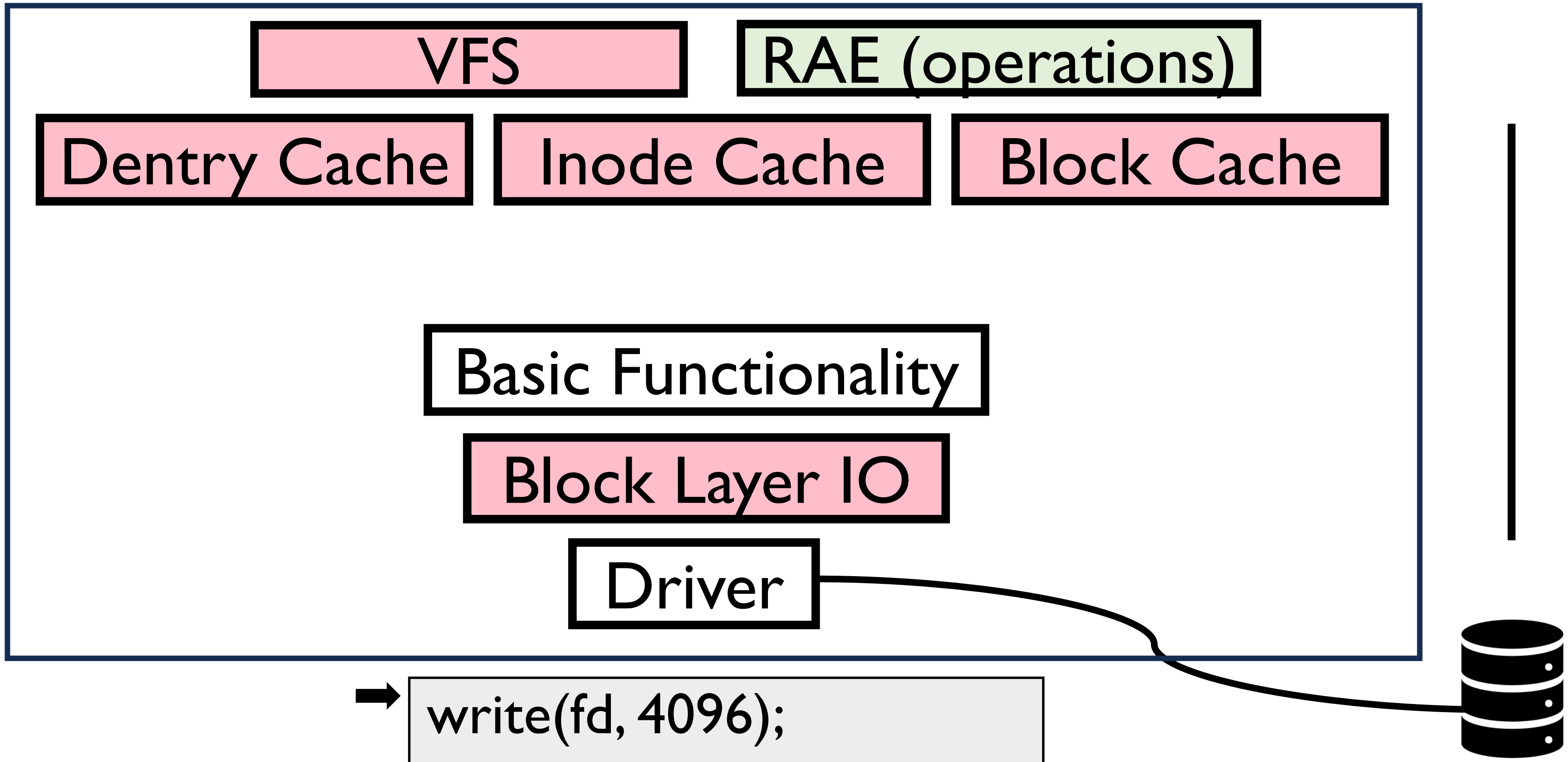
Base (common path)

- An existing filesystem optimized for performance

Shadow (alternative path)

- A shadow filesystem that aims to be "bug-free"

Base Executes the Workload




```
write(fd, 4096);
write(fd, 4096);
pread(fd, offset=0);
close(fd);
```

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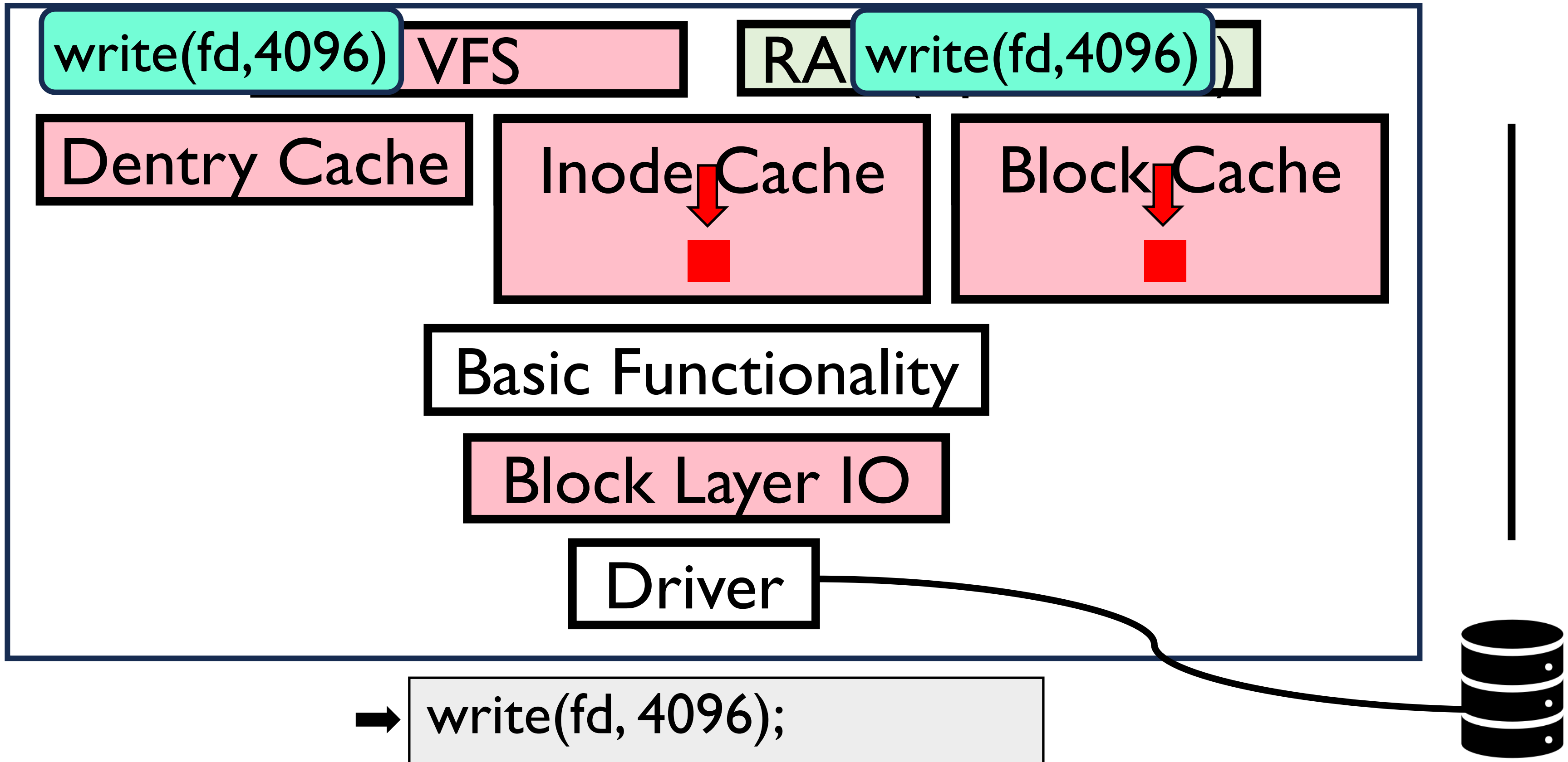


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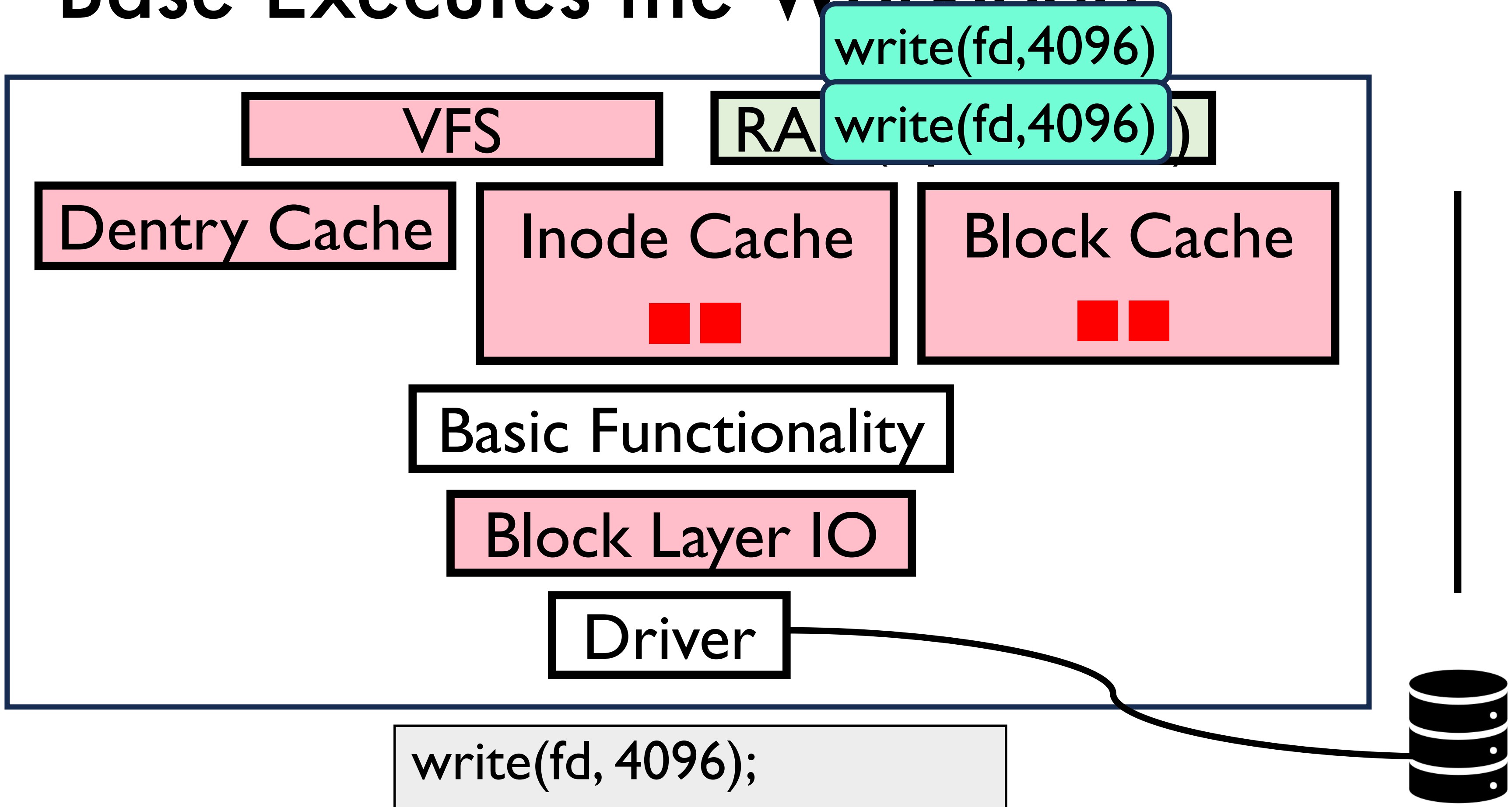


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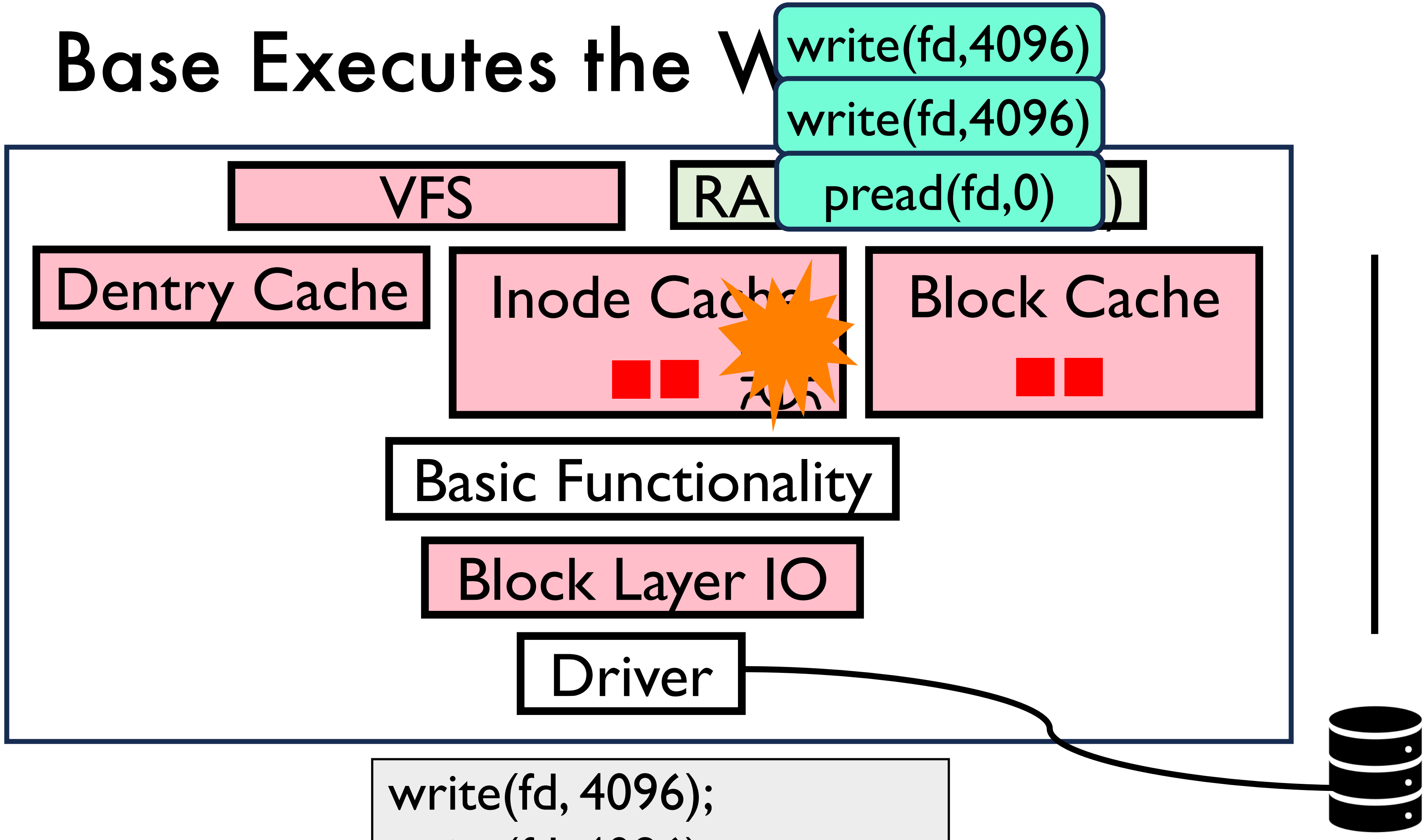


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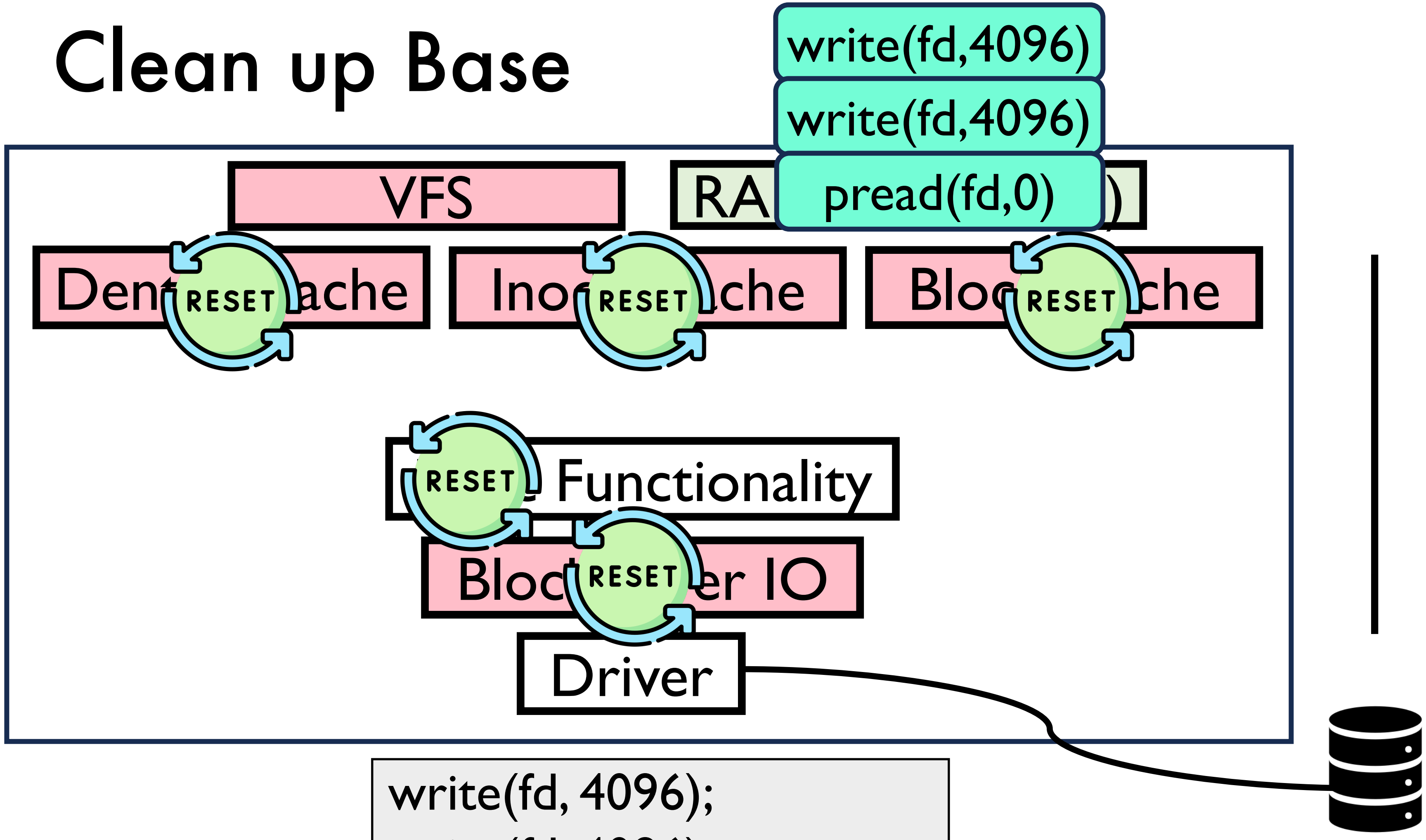
Clean up Base

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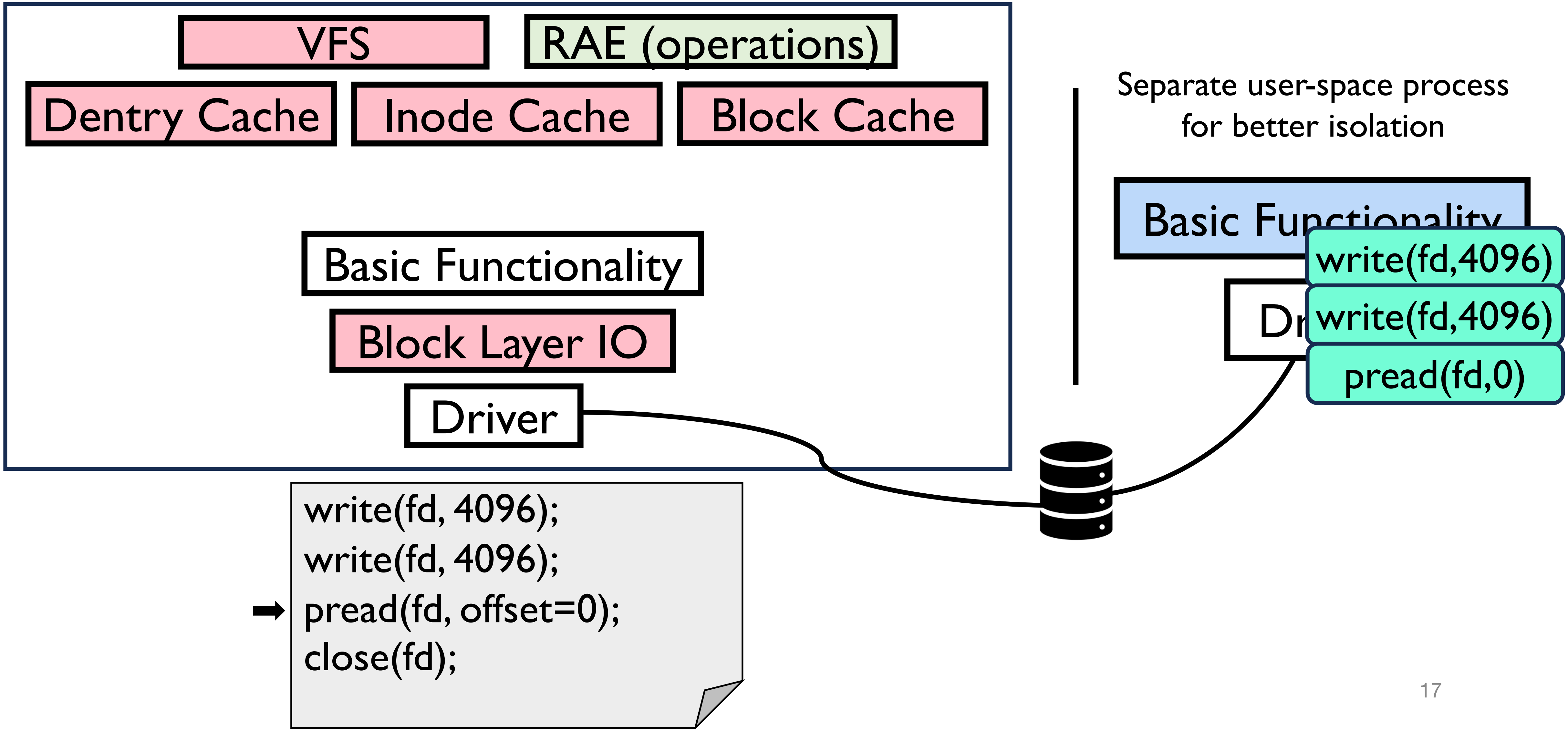
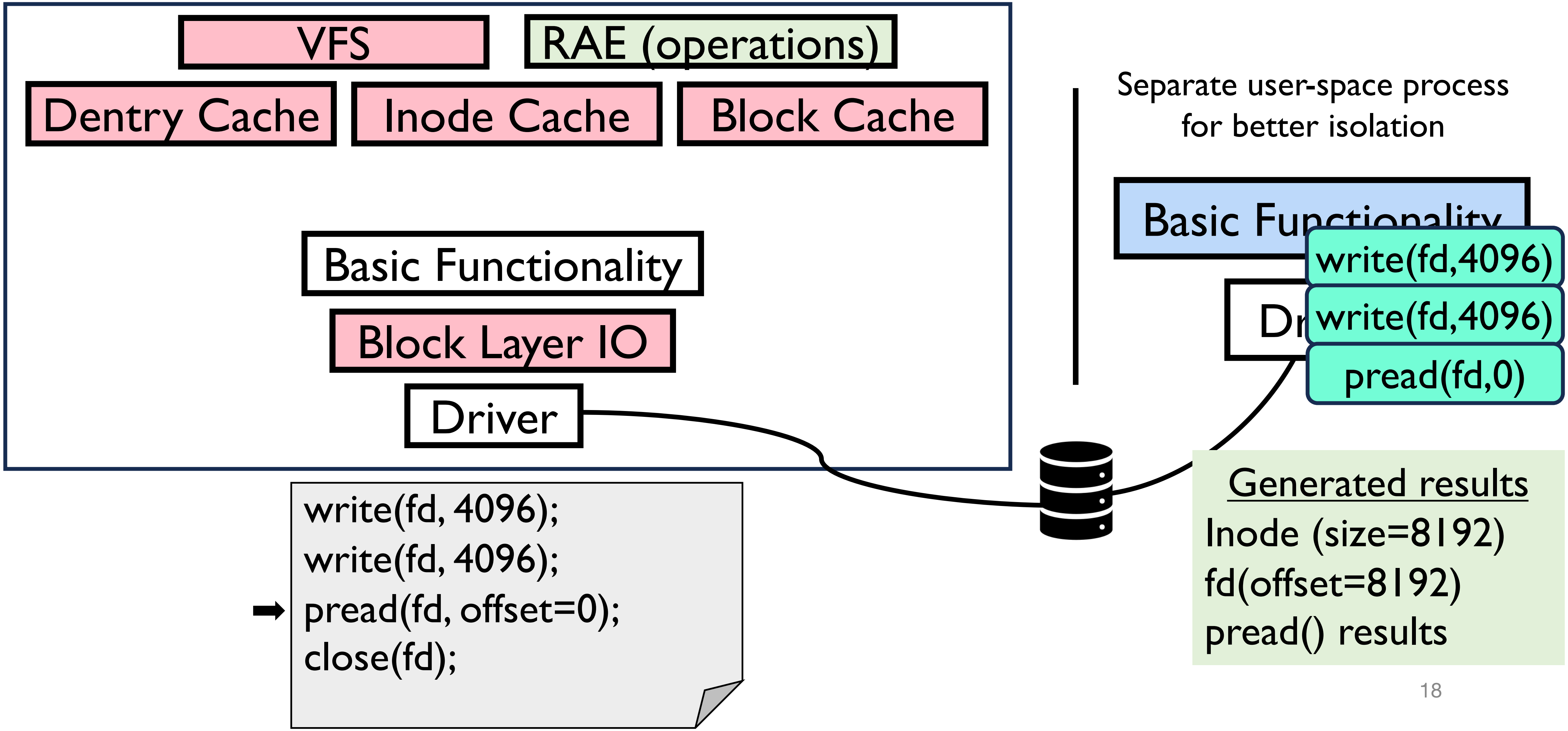
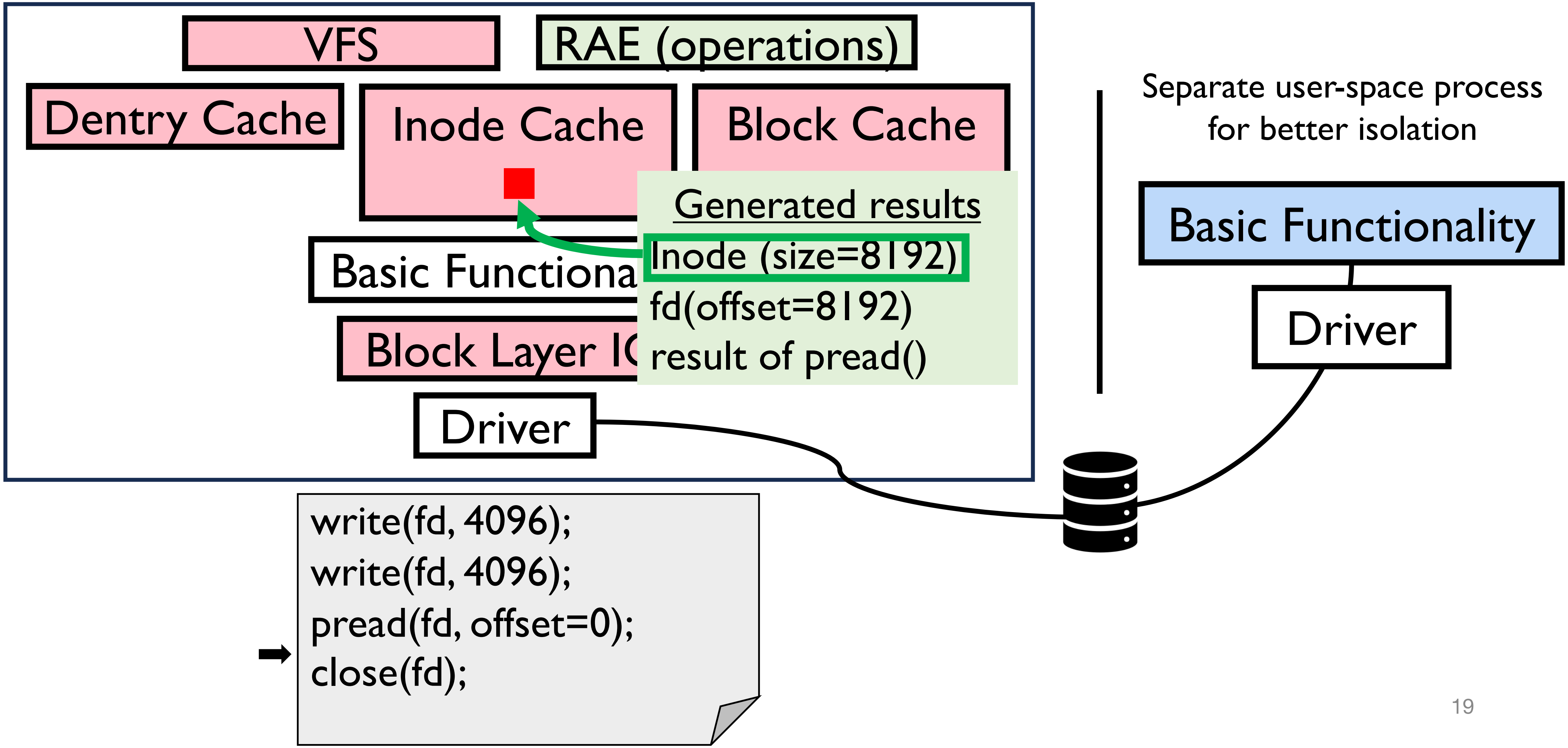
Hand-off to Shadow



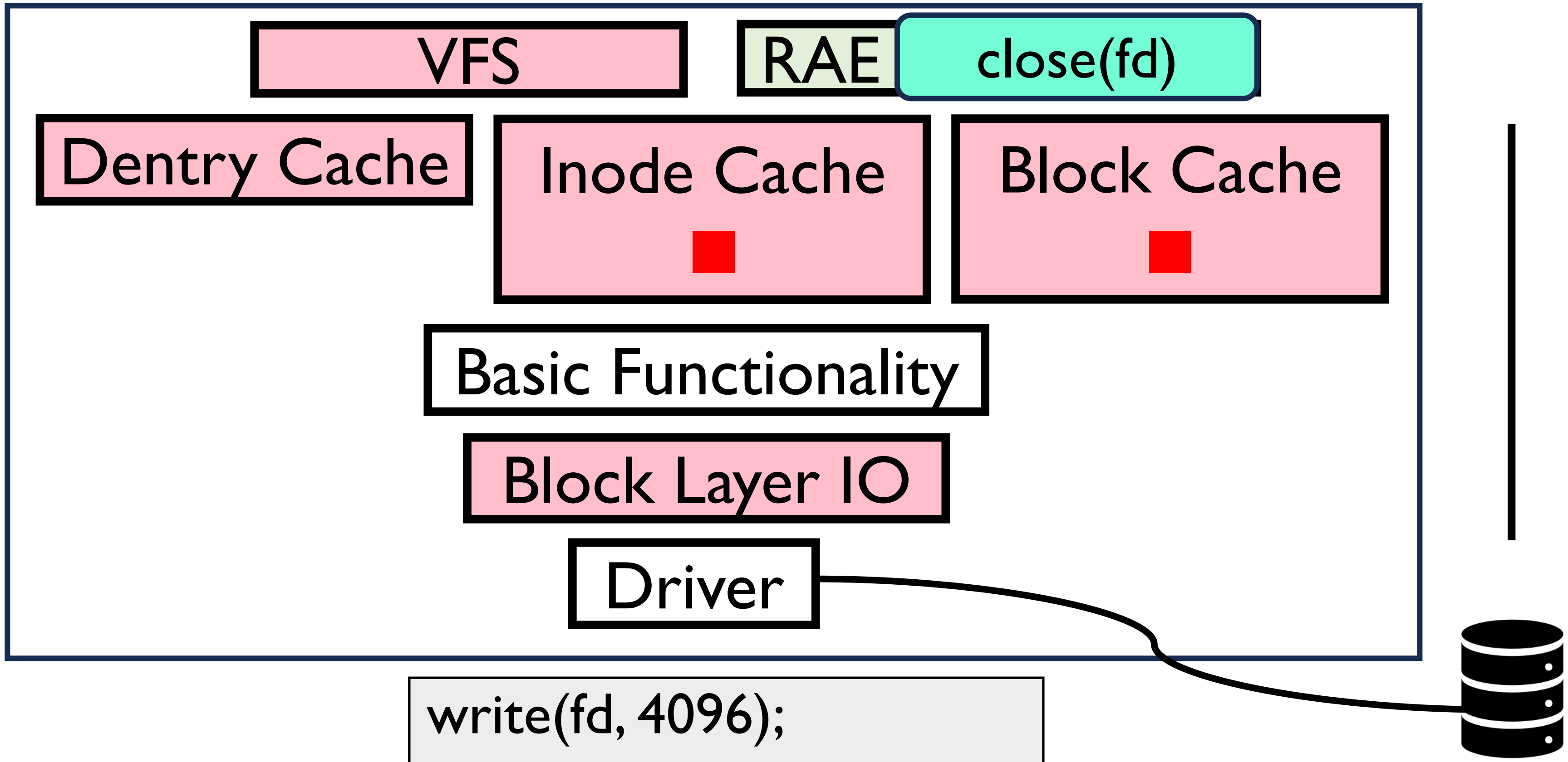
Shadow Executes the Workload, Correctly!



Base Obtains the Results



Base Continues

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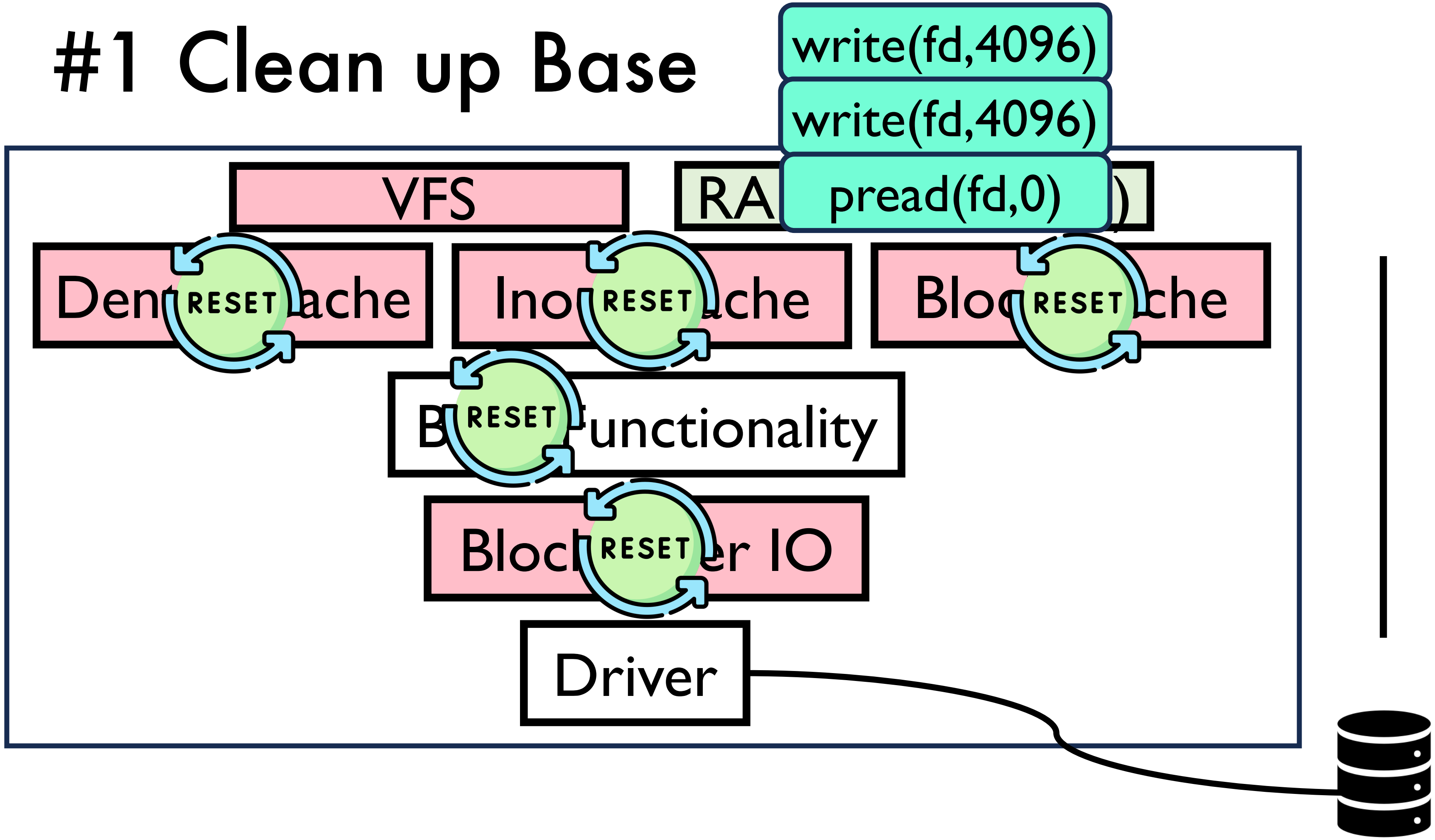
Challenges

#1 Clean up the base

#2 Correctness of the shadow

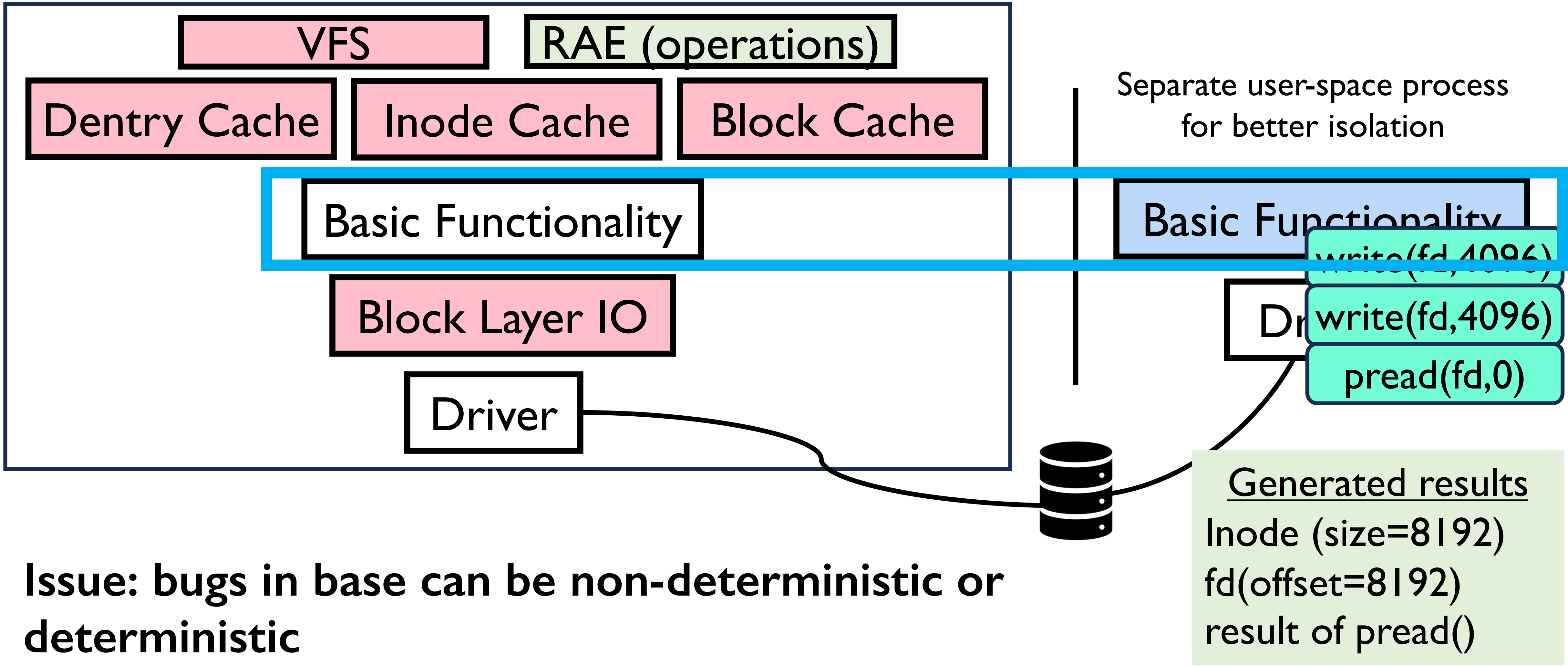
#3 Base obtains the results

#1 Clean up Base



Issue: reset the base components without restarting the OS to clean up buggy states

#2 Correctness of the Shadow



Issue: bugs in base can be non-deterministic or deterministic

A Deterministic Bug in ext4 (CVE 2022-1184)

```
#/bin/bash
mount -o loop tmp32.img mnt  # a corrupted image
mv mnt/foo/bar mnt/foo/YzoUYCy4vTth45i7... ZIOFz
mv mnt/foo/YzoUYCy4vTth45i7... ZIOFz  mnt/foo/AIdkBBulG0Pp5lbV... 7oF
```

> A use-after-free flaw was found in fs/ext4/namei.c:dx_insert_block() in the Linux kernel's filesystem sub-component. This flaw allows a local attacker with a user privilege to cause a denial of service.

Deterministic bugs are challenging to recover from

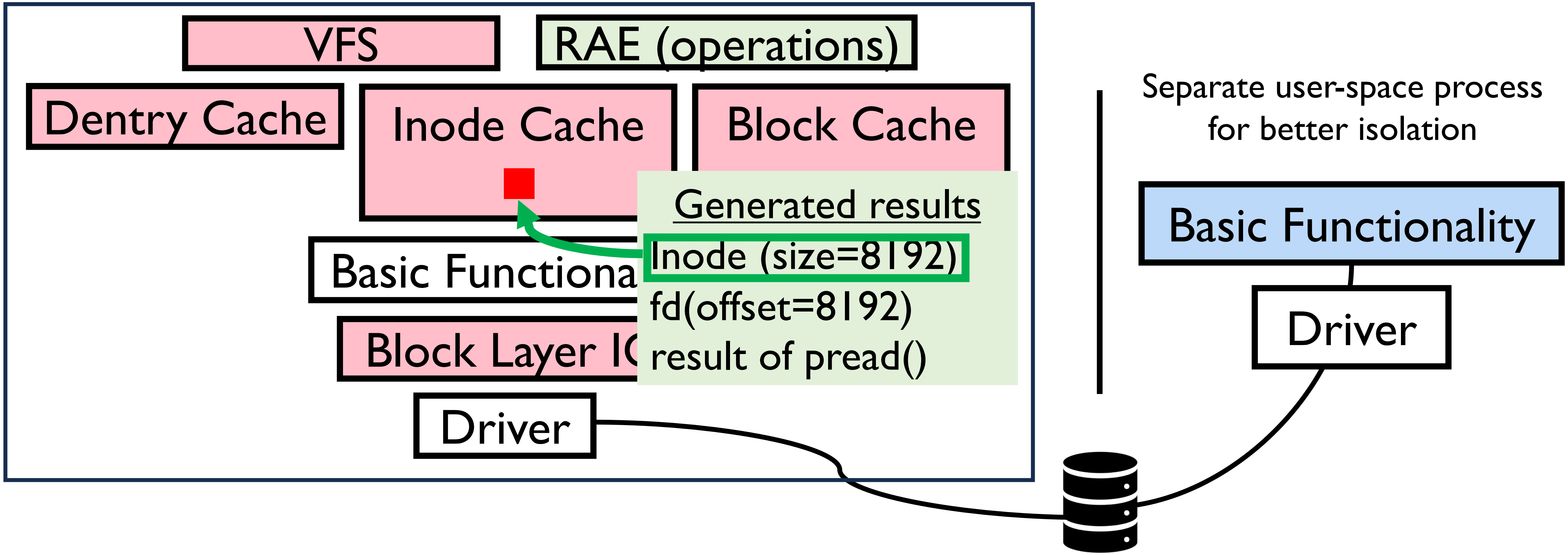
- retry by the base will fail again
- shadow's benefit

#2 Correctness of the Shadow

Techniques

- **A much simpler implementation from scratch**
  - Only basic functionality
  - Without any performance component
- **Fully-verified implementation is practical**
  - “Simple” enough for verification
  - Implementation from scratch makes verification easy

#3 Base Obtains the Results



Issue: base needs to continue with shadow's output

#3 Base Obtains the Results

Techniques

- Metadata downloading
  - Base directly reads the results from known directory (e.g., in /tmp/inodes), but not from disk
    - Shadow never writes to disk
  - Base exposes APIs to read shadow's output
    - E.g., InitInodeCache(path=/tmp/inodes)

Three Challenges

#1 Clean up the base

- reset all components in the base without restarting the OS

#2 Correctness of the shadow

- simple implementation from scratch and fully-verified

#3 Base obtains the results

- new API in base to read from (in-memory) temporary files

Prototype and Progress Status

Prototyping in uFS

- A high-performance microkernel style filesystem (SOSP '21)
- Clean up the base
  - restart the process is enough
- Correctness of the shadow
  - 35K Loc C++ (base) vs. 2.5K Loc Rust (shadow)
  - Verification of the rust implementation is in progress
    - Verus: automatic prover for rust language

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Testing the discrepancies

- Given a workload, what if shadow and base produce different results?

Future Challenges

Testing the discrepancies

Trusted code

- The interaction between base and shadow
  - Hand-off
  - Downloading

Future Challenges

Testing the discrepancies

Trusted code

Design the shadow to be friendly to verify

- Interesting issues due to Rust's interaction with driver (i.e., C code)
- On-disk format is within the specification
  - E.g., handle crafted image

Future Challenges

Testing the discrepancies

Trusted code

Design the shadow to be friendly to verify

Maintain the shadow while the base evolves

- Shadow can be a “simple enough spec.” to evolve as well
- An up-to-date document

Future Challenges

Testing the discrepancies

Trusted code

Design the shadow to be friendly to verify

Maintain the shadow while the base evolves

Linux kernel filesystems

- “Reset the base without restarting the OS” and “Metadata downloading” are more challenging
- Each base (ext4, btrfs) needs one shadow

Summary

Robust Alternative Execution

Two filesystems to achieve both high performance and correctness

- An existing base: optimized for performance
- Build a shadow
  - From scratch
  - Avoid any performance optimization
  - Fully-verified implementation
- Coordination between base and shadow

Summary

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Thank you!