Optimizing Storage and Memory Systems for Energy and Performance

Luis Useche

Dissertation Defense, July 2012

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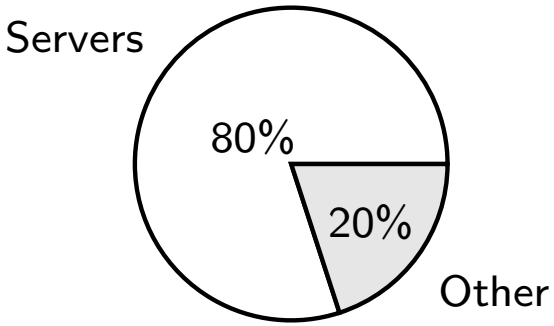
Datacenters Power Breakdown



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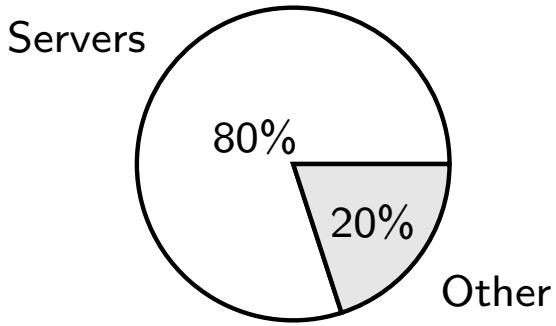

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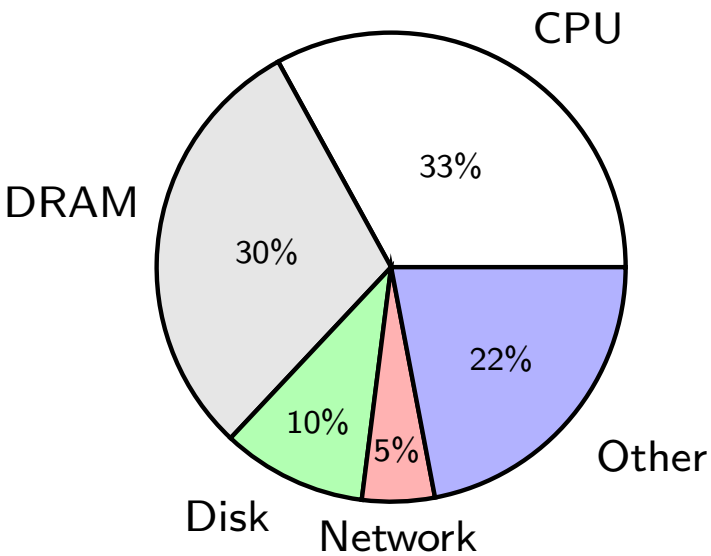

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- Or $144 Million
- Worse with increasing DRAM and storage needs

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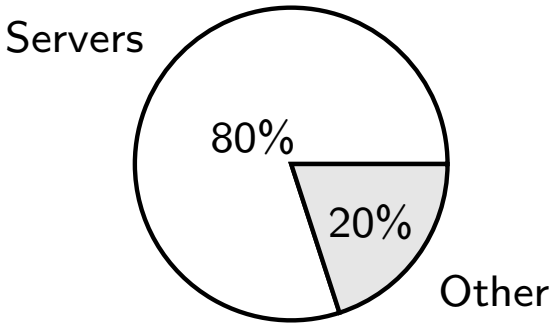

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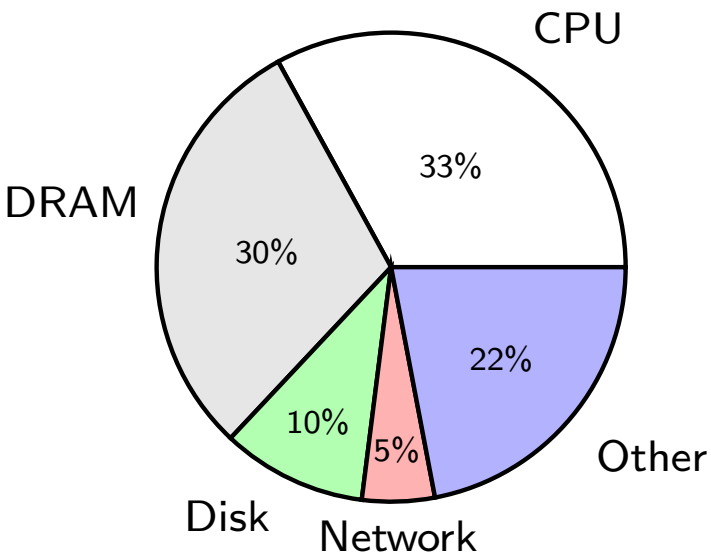

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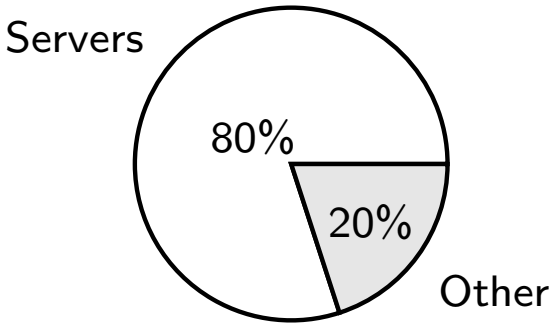

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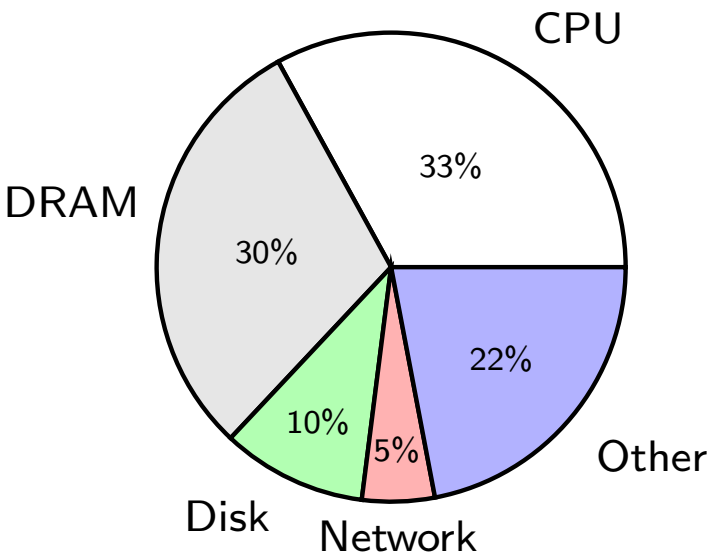

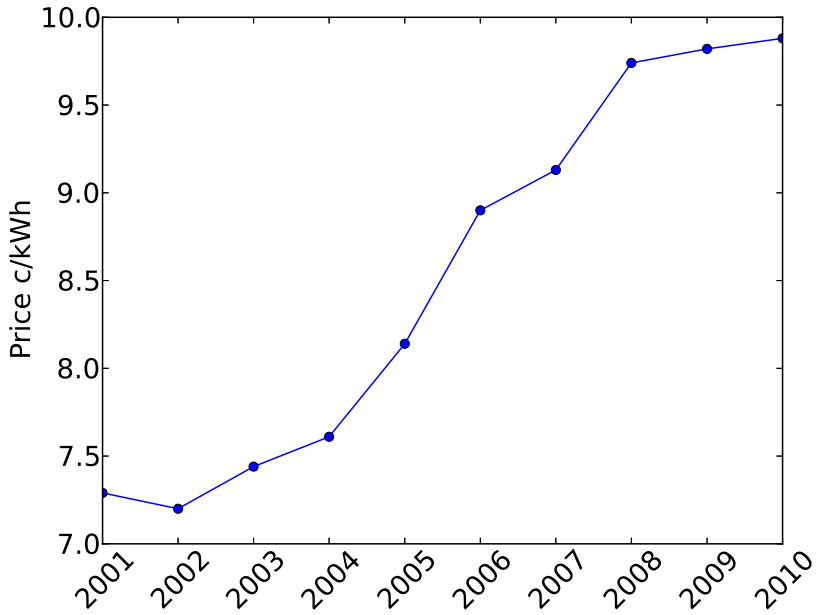

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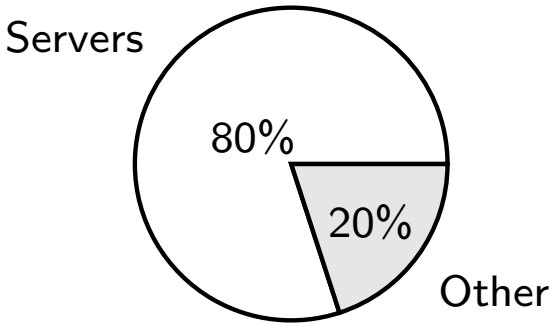

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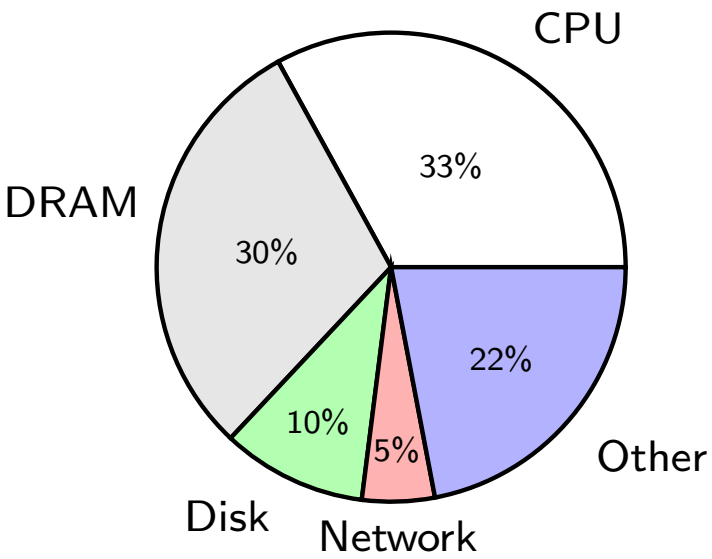

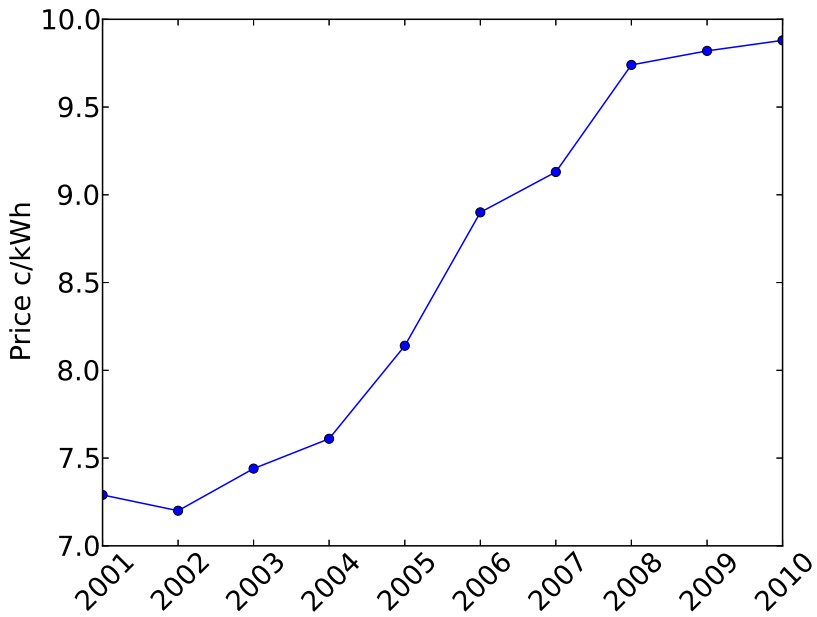

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- Reduce data-centers operation cost
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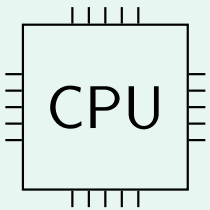

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- Lower power levels $\Rightarrow$ Lower performance

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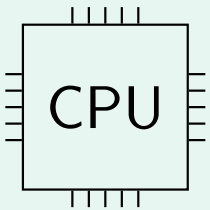

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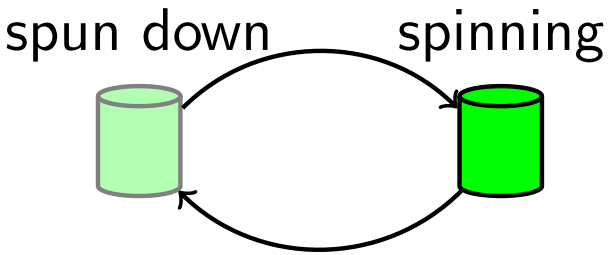
Example

- It continuously refreshes itself even when idle
- Exchanging DRAM for flash would increase paging activity

Disks are not energy proportional



- Two power consumption levels
- Can only save power when not rotating (spun down)
- Accesses while spun-down incur in delays of seconds
- Constant power consumption while spinning

Solutions

Disk

1. Spin-down the disk when not in use
   - ✓ Requests incur delay waiting for the disk to spin-up
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   - ✓ Requests incur delay waiting for the disk to spin-up
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2. Aggressive power-aware DRAM caching **[Axboe 04]**
   - ✓ Memory may not be big enough to hold the working set of a long time
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3. External Caching **[Marsh et al. 94]** $\Leftarrow$ **Simulation**
4. On multi-disk systems, duplicate data and use fewer disks **[Pinheiro et al. 04]** $\Leftarrow$ **No proportionality**

Memory

1. Increase locality in DRAM **[Sudan et al. 10]** $\Leftarrow$ **Idle Power**
2. Use multi-power DRAM **[Deng et al. 11]** $\Leftarrow$ **Idle Power**

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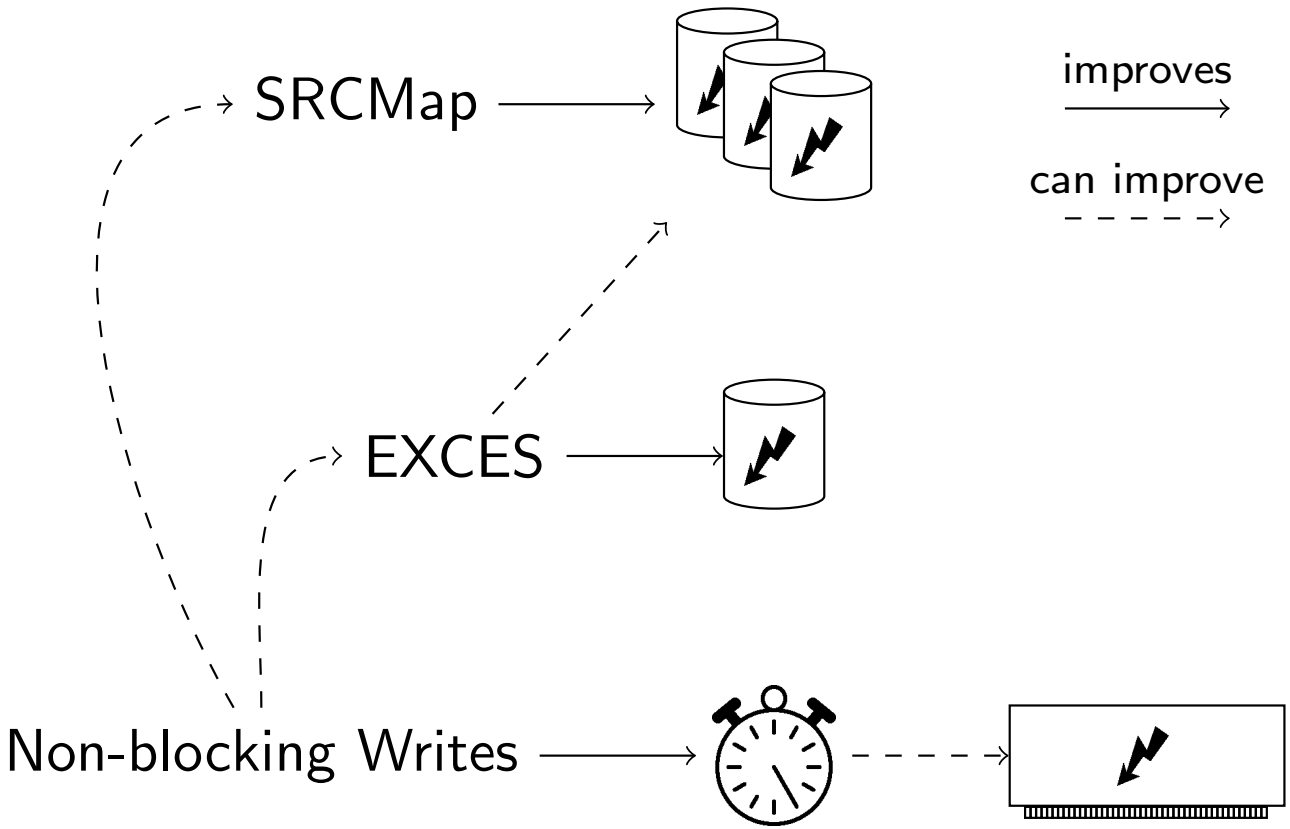
- designing and implementing energy-efficient storage systems using flash devices as an external cache to reduce energy consumption in disks (EXCES), and
- designing and implementing a new mechanism to eliminate blocking read page operations due to page writes that could, otherwise, disturb disks in their low-power state and slowdown applications (Non-blocking Writes).

Contributions



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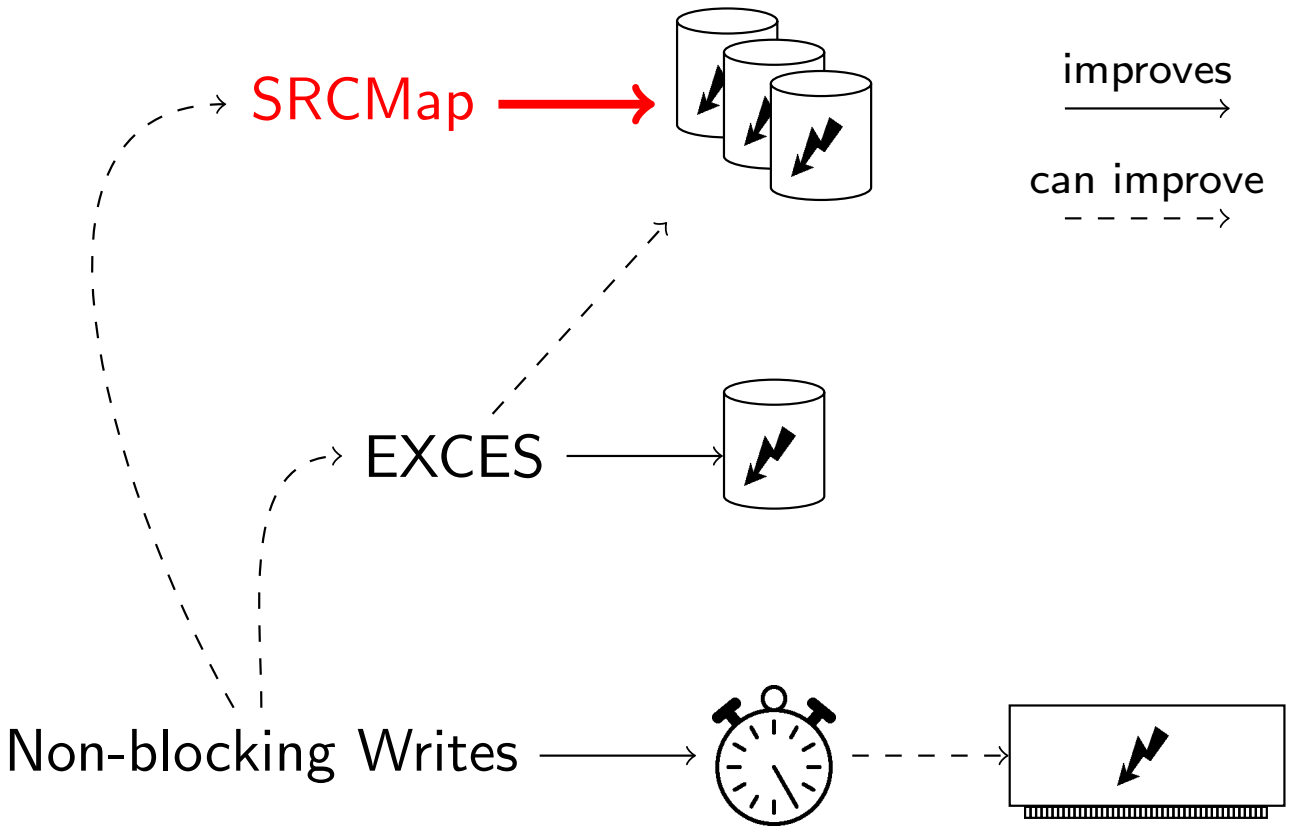

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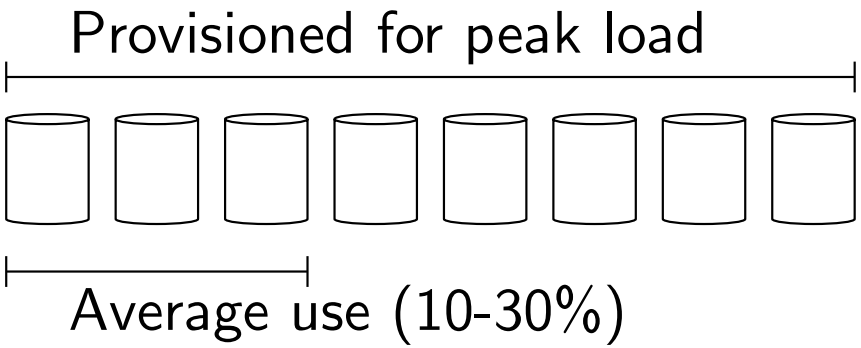

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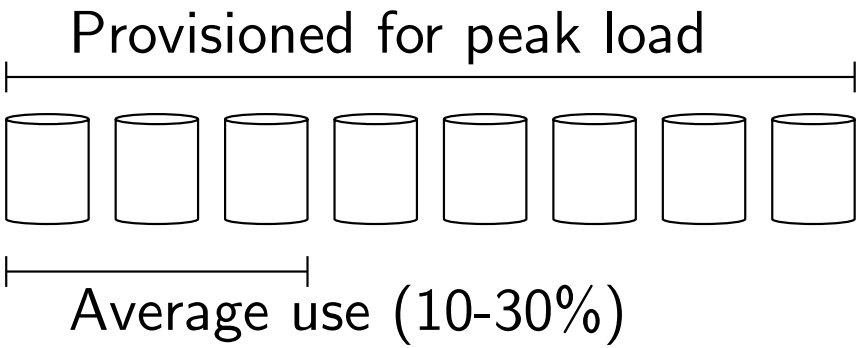

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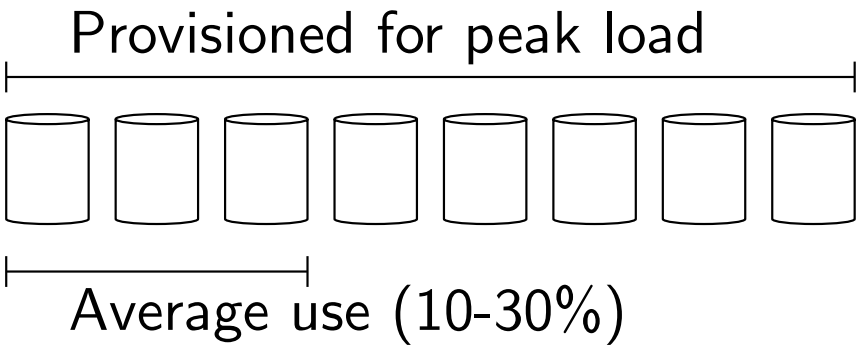


- Consolidation is a well known technique for energy proportionality in virtualized servers

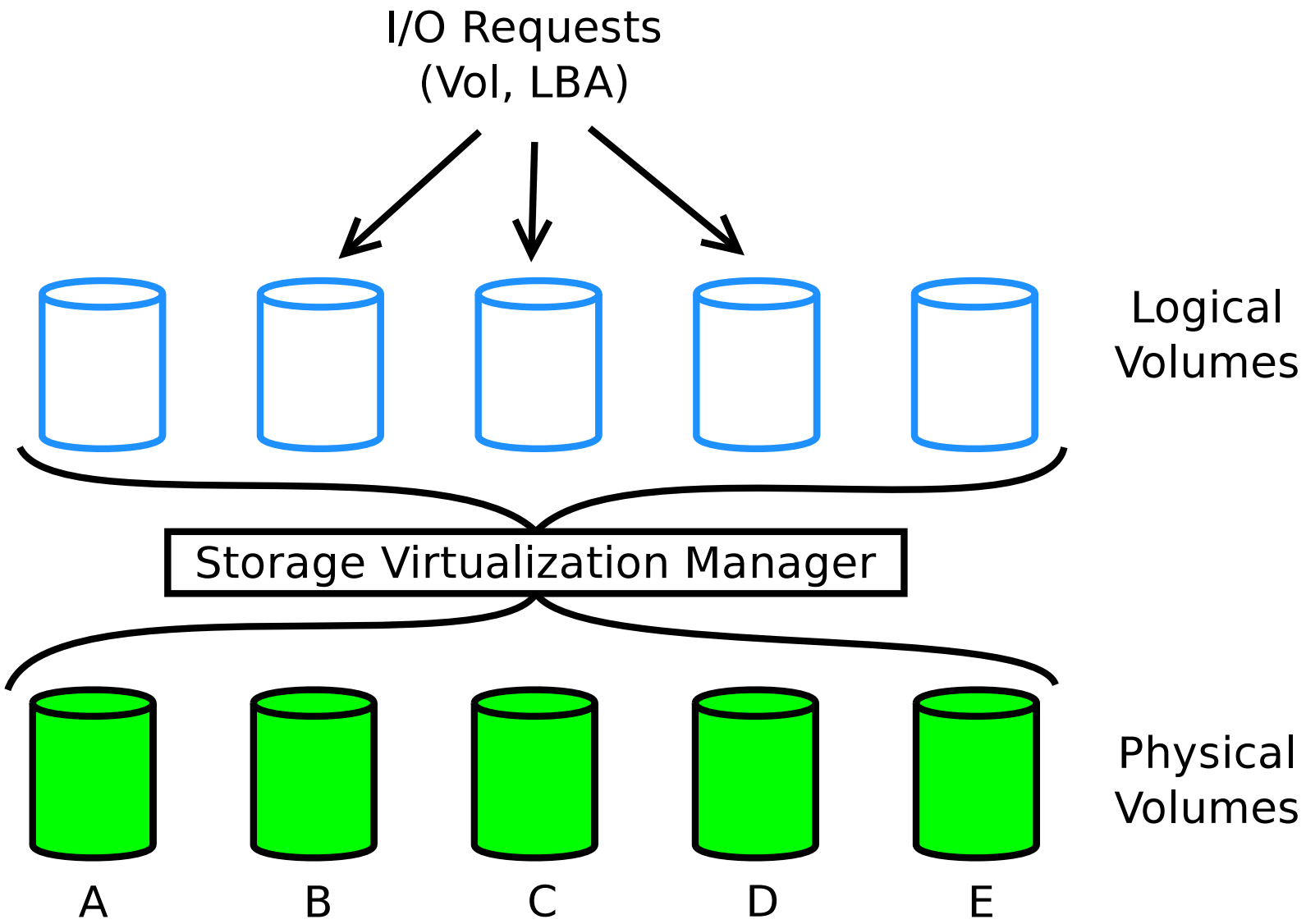
Can we use a storage virtualization layer to design a practical energy proportional storage system?

- Storage virtualization I/O indirection useful for consolidation.

Challenge

Moving logical volumes from one device to another is prohibitively expensive.

SRCMap: Overview



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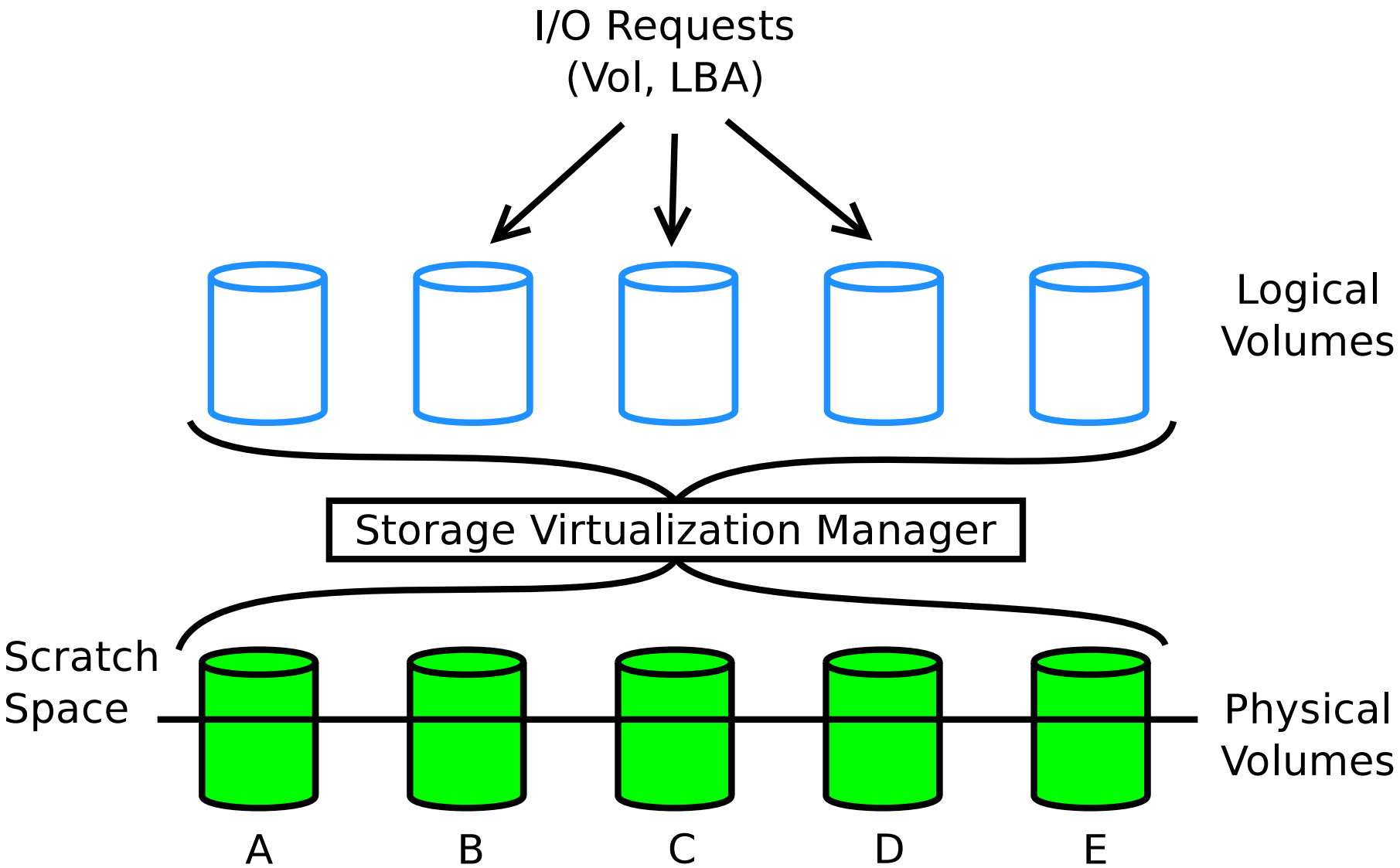

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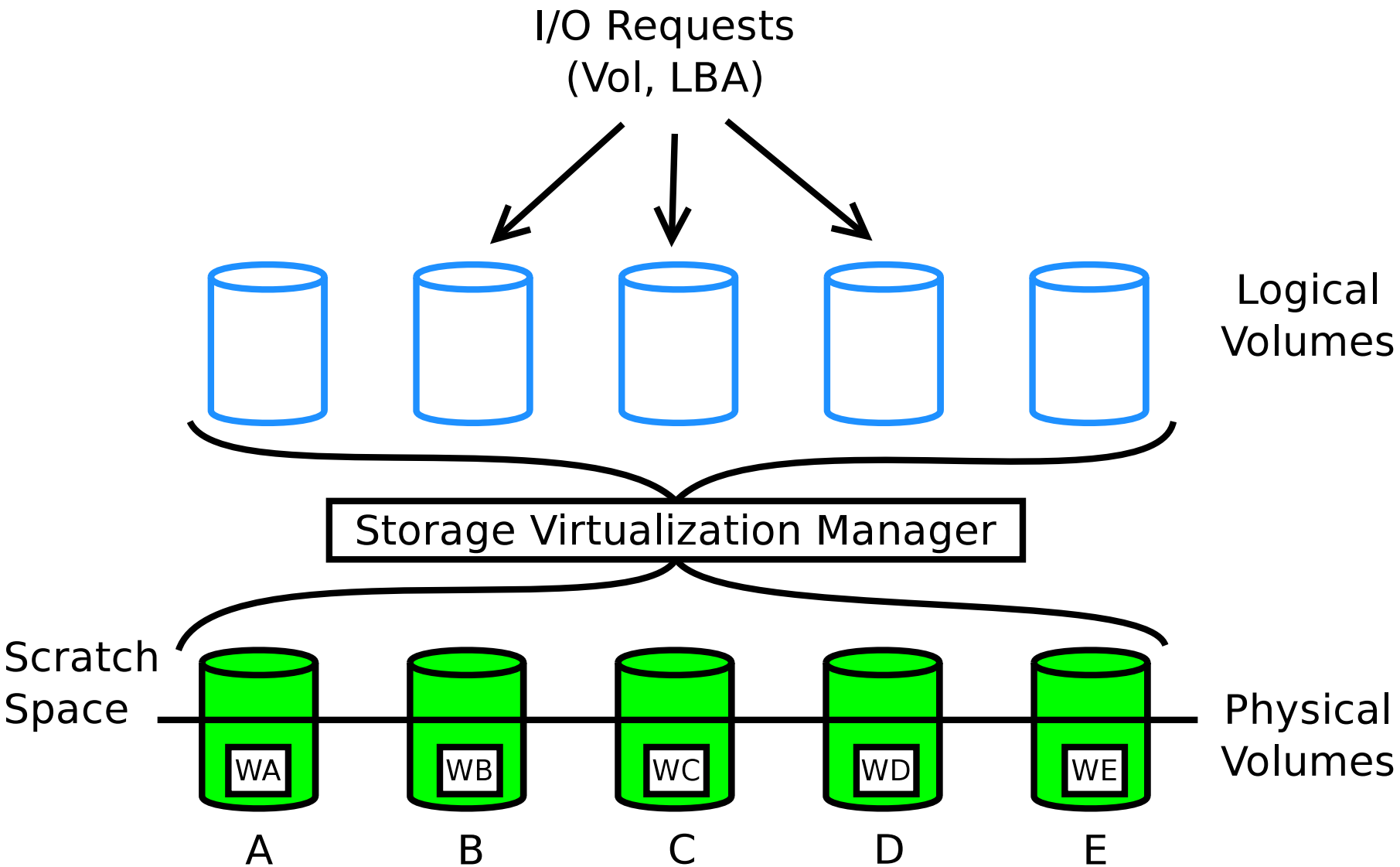

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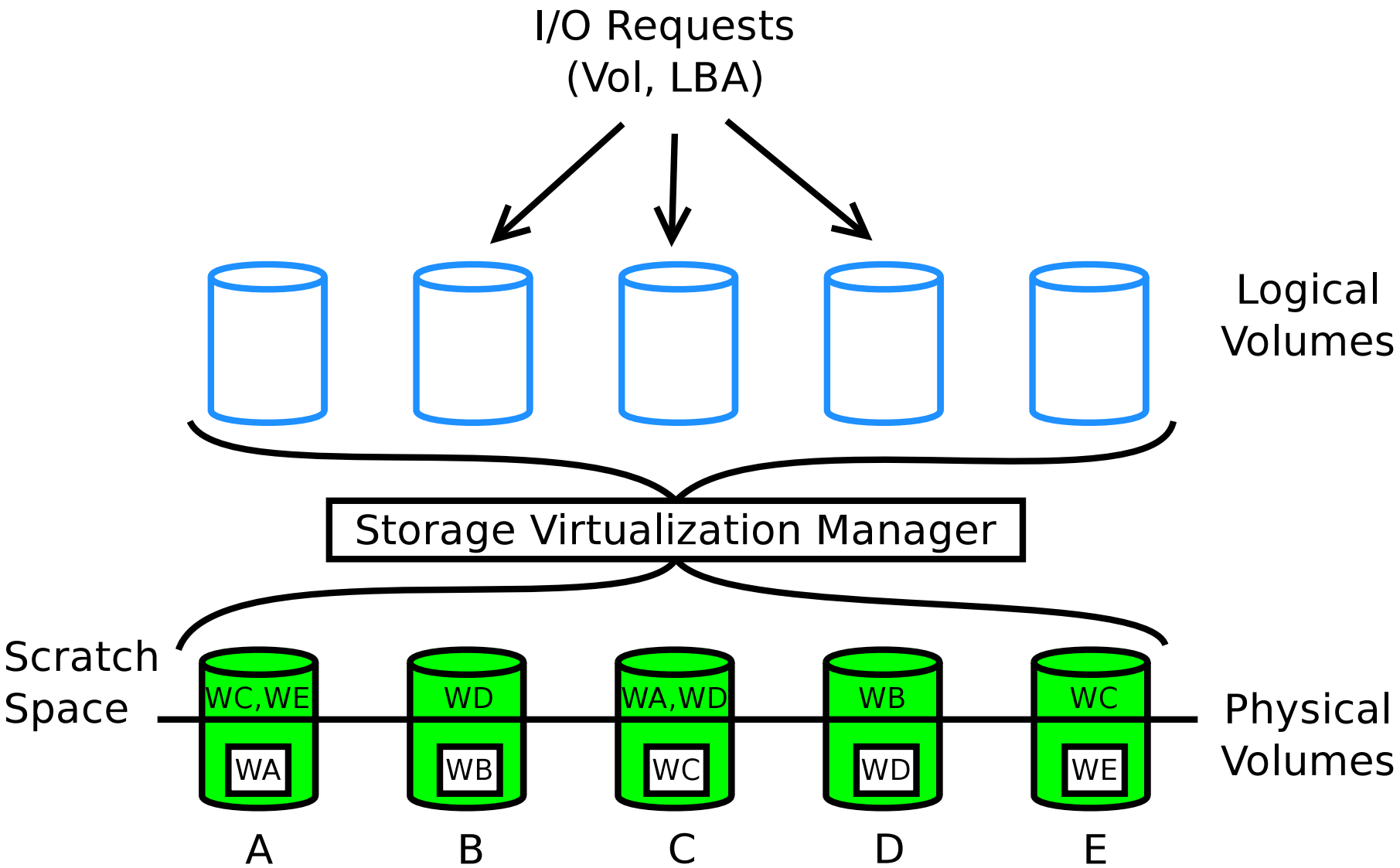

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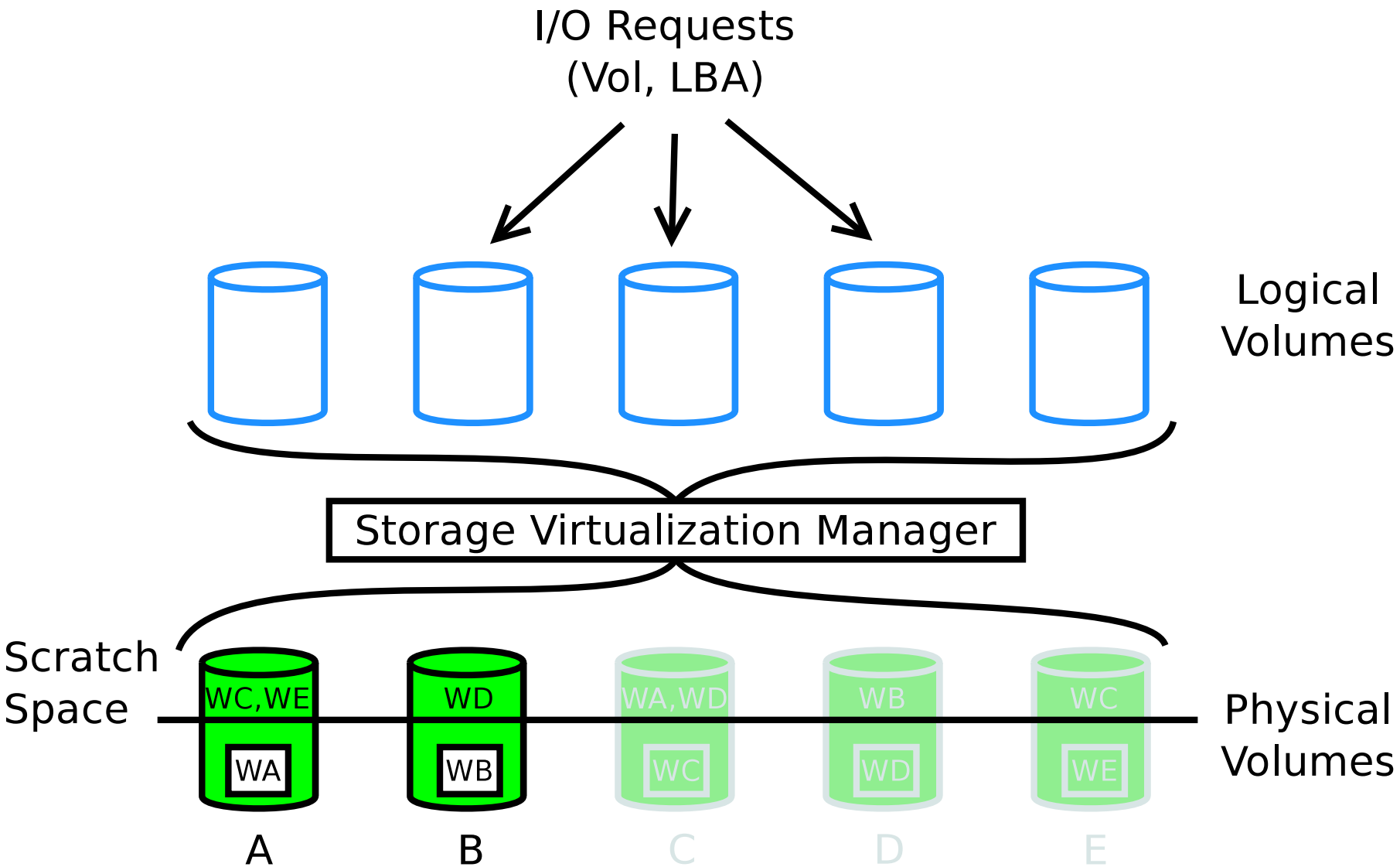

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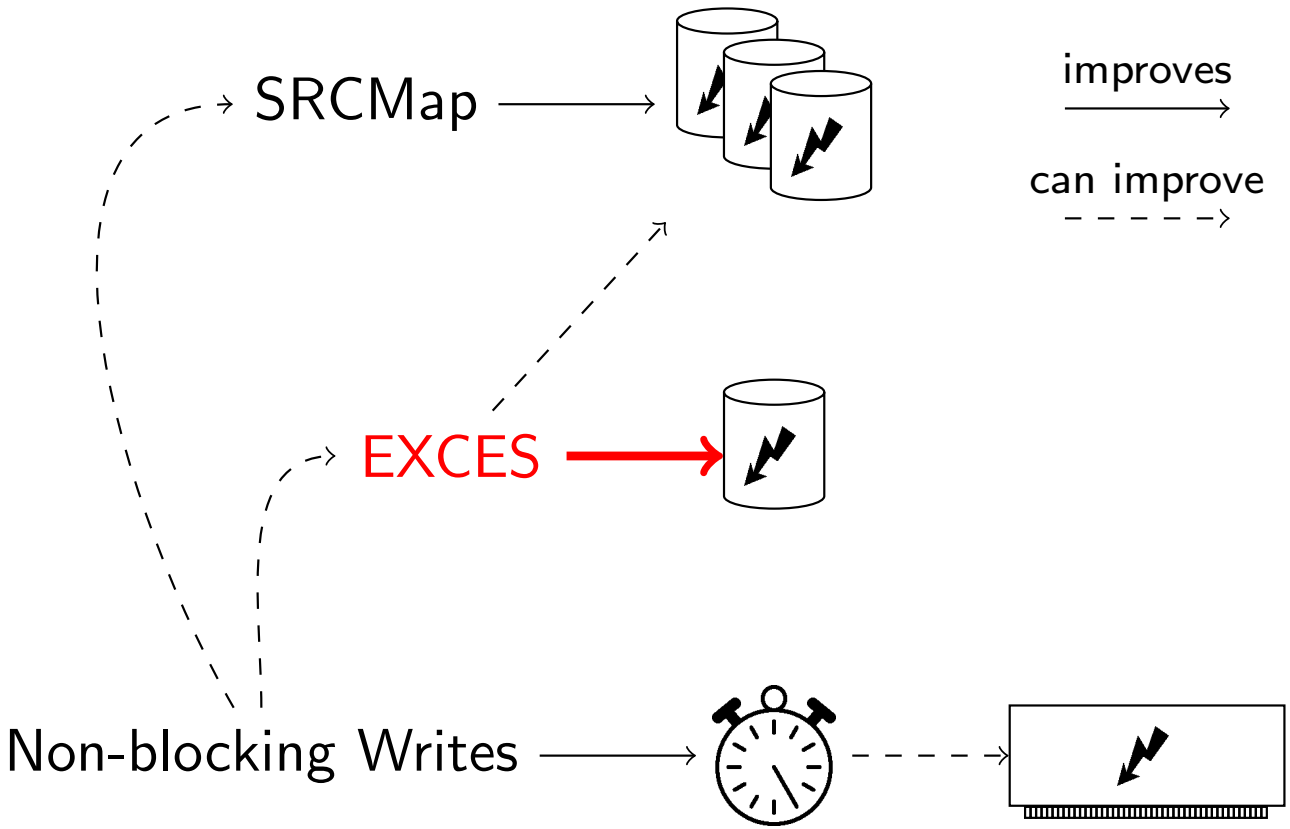

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Goals

- Increase disk inactivity by: caching, prefetching, and write buffering in flash device
- Make effective use of external flash caching by adapting to workload changes
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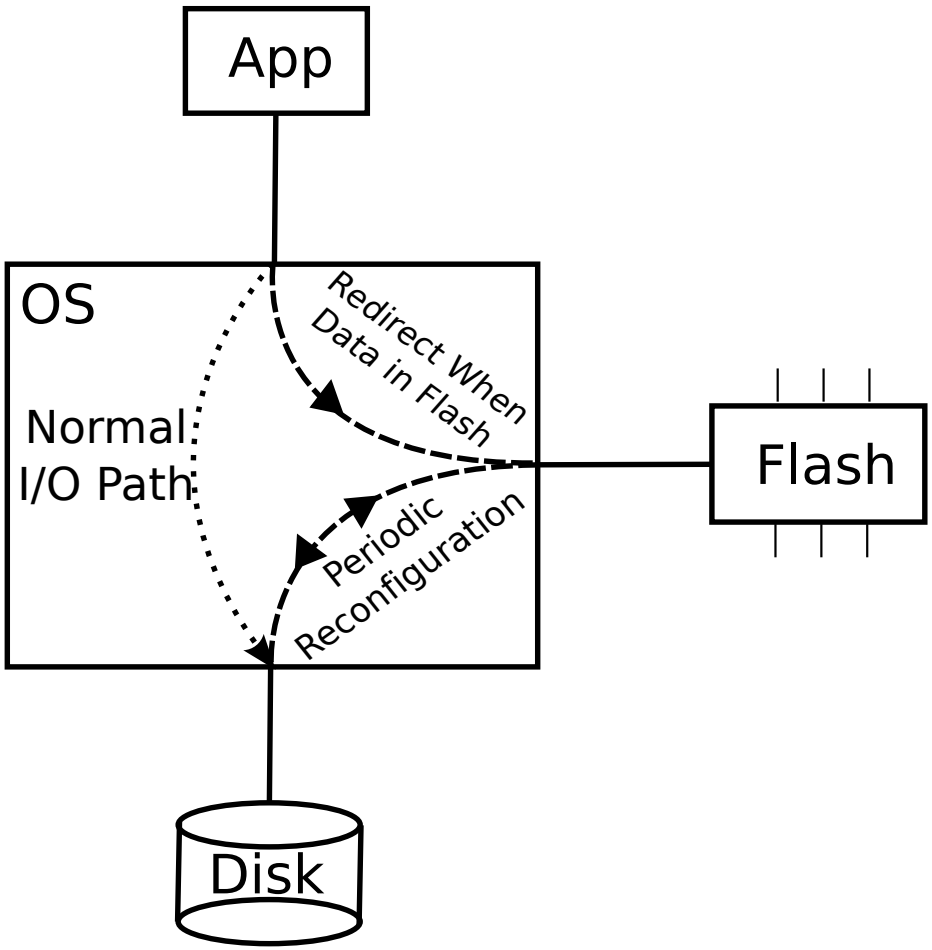

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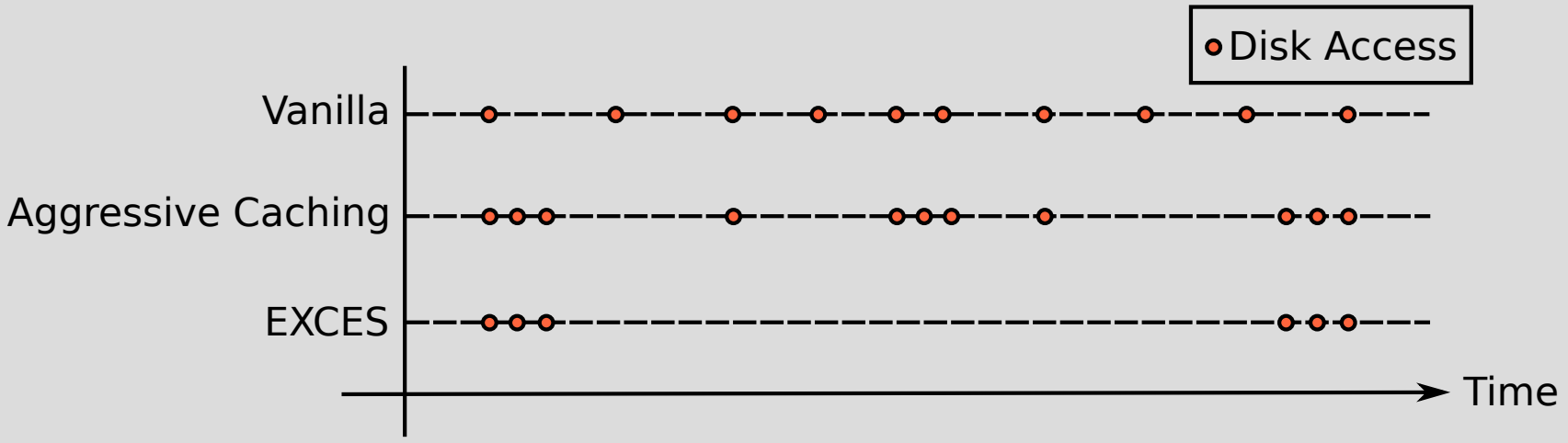

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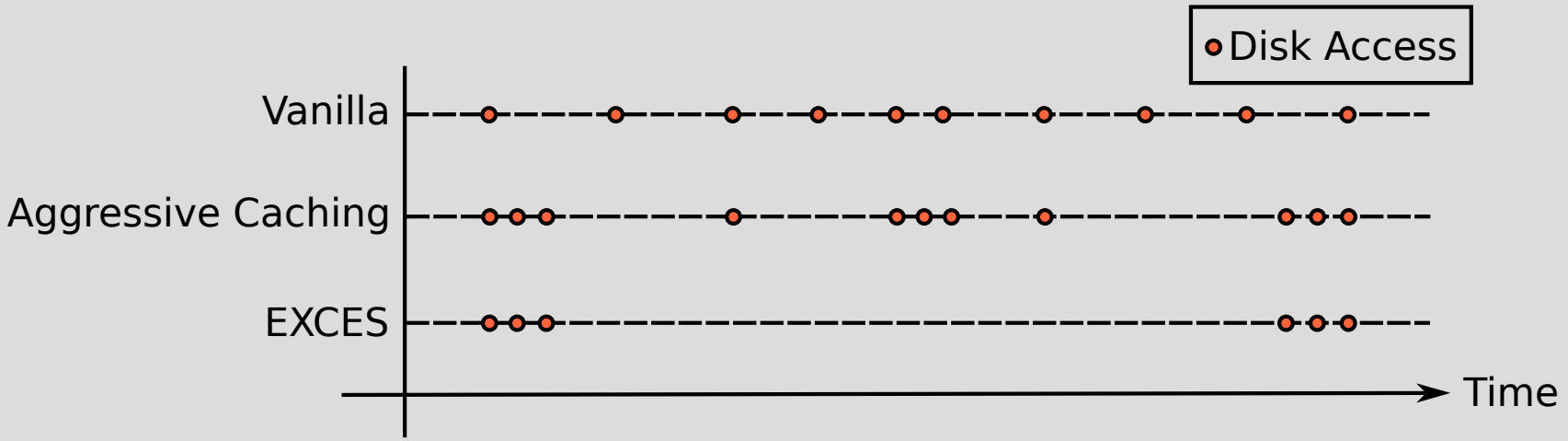

- First implementation of energy efficient external caching
- We designed and implemented EXCES for Linux
- We evaluated EXCES in a laptop using:
  - ✓ USB and CF external device
  - ✓ Desktop, developer, and server workloads

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- ▶ Better energy efficiency in mobile devices by simply plugging an external device

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- Both SRCMap and EXCES are cache systems
- Their effectiveness depends on the number of cache hits
- Caching is performed at page granularity

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Handling Misses

- Reads to non-cached pages still require disk attention
- Full-page writes can be buffered in cache
- Sub-page writes require disk attention

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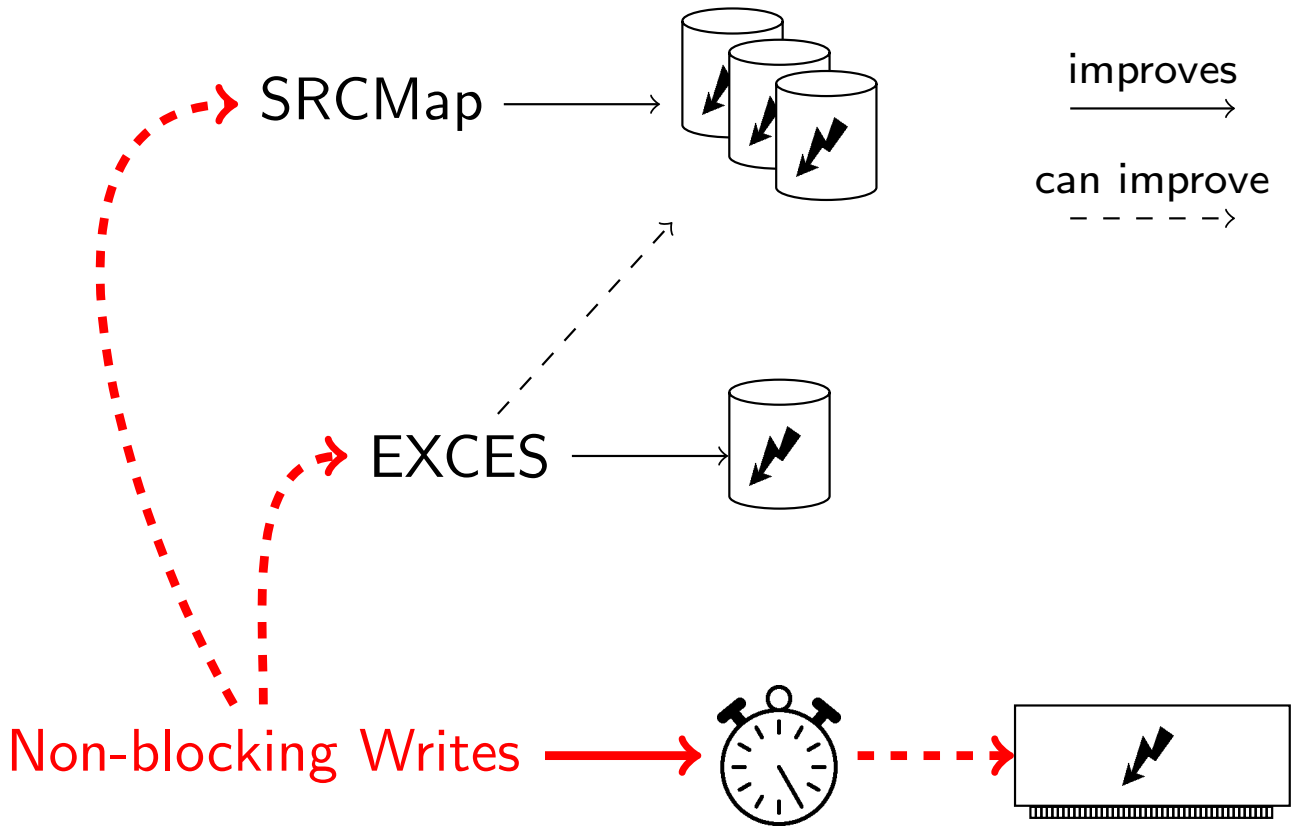

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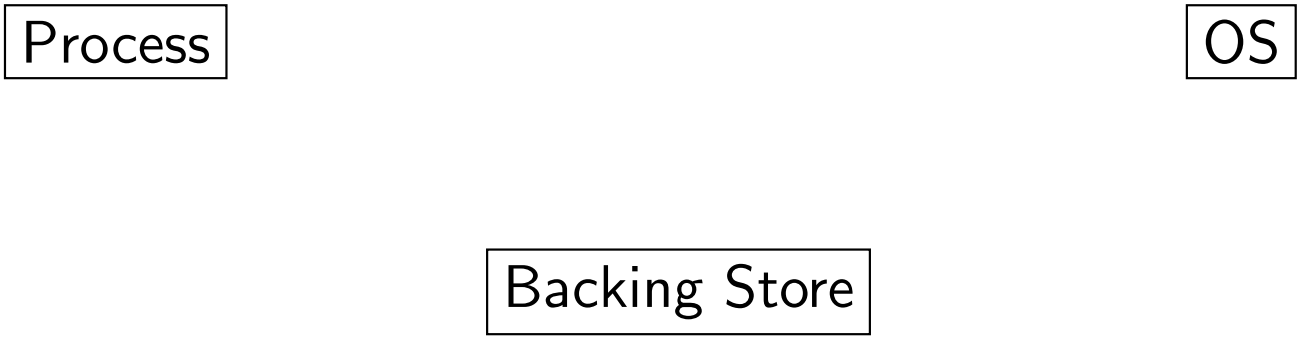

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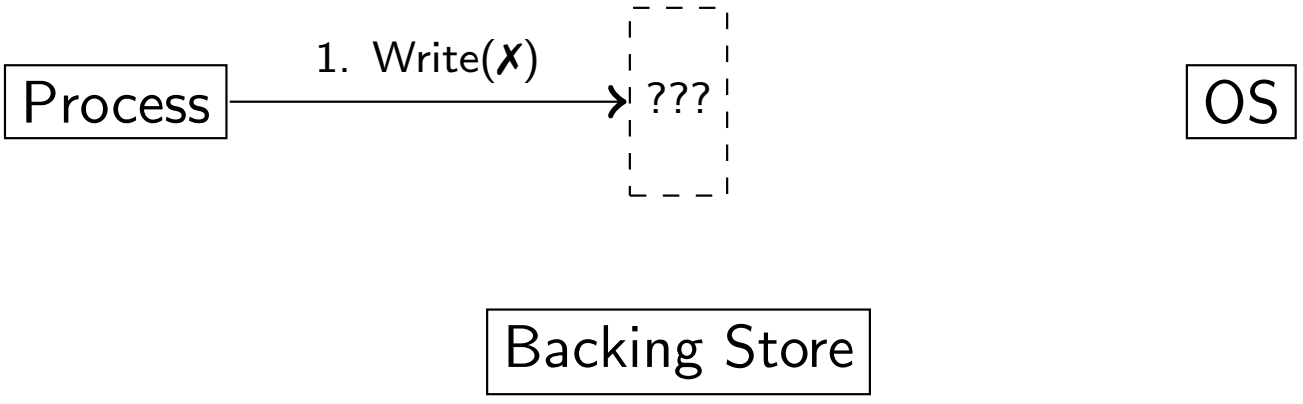

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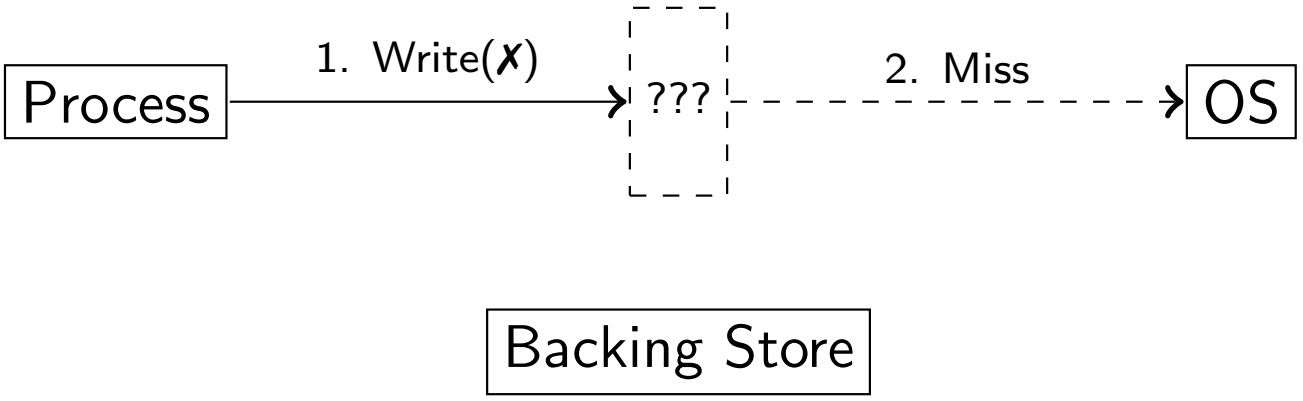

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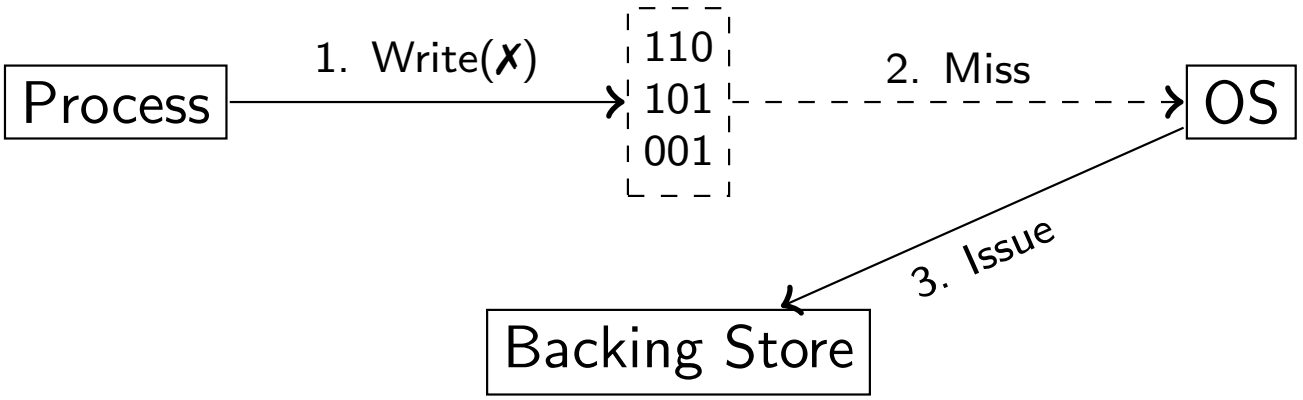

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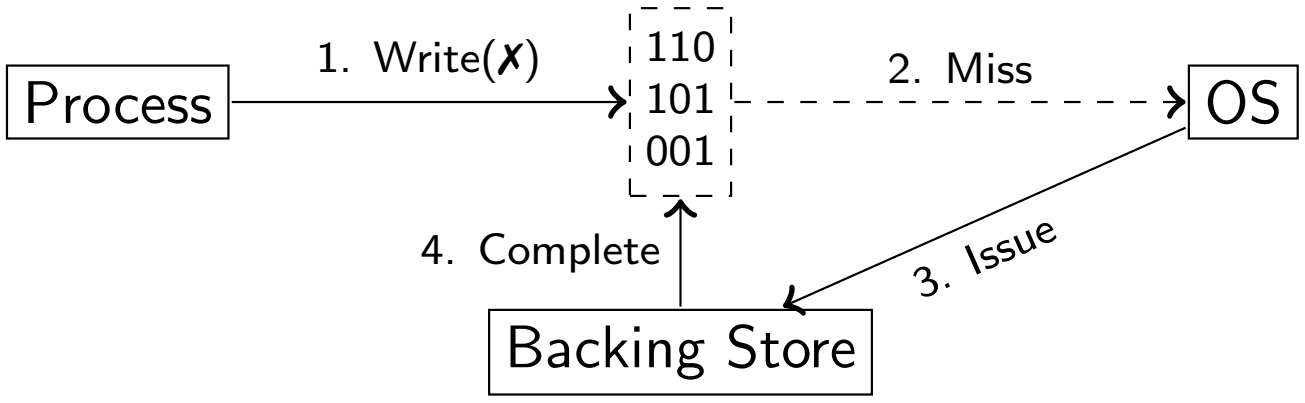

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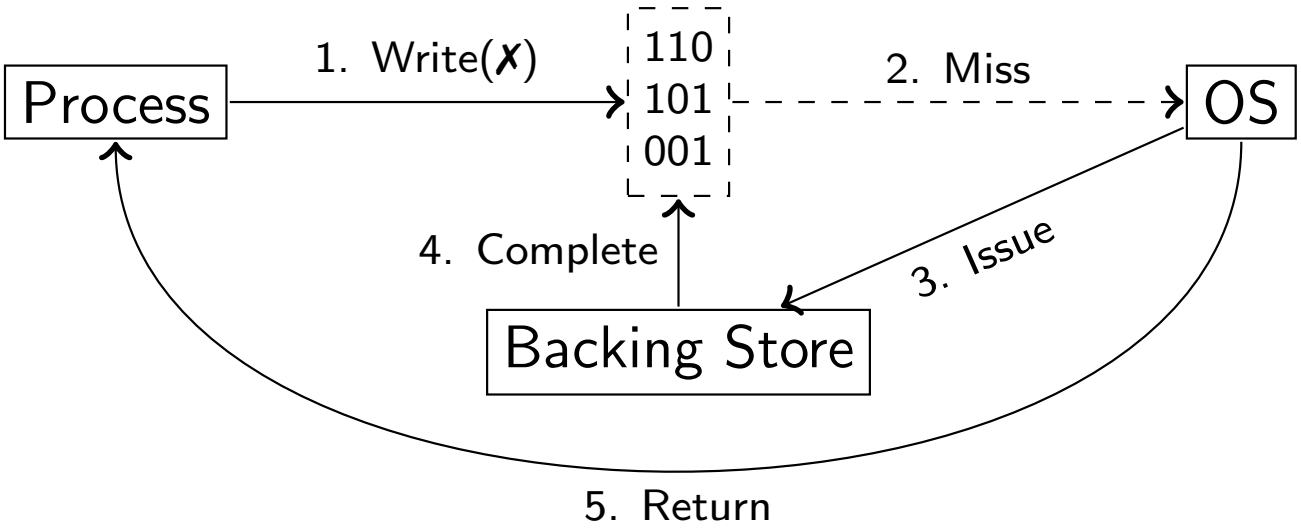

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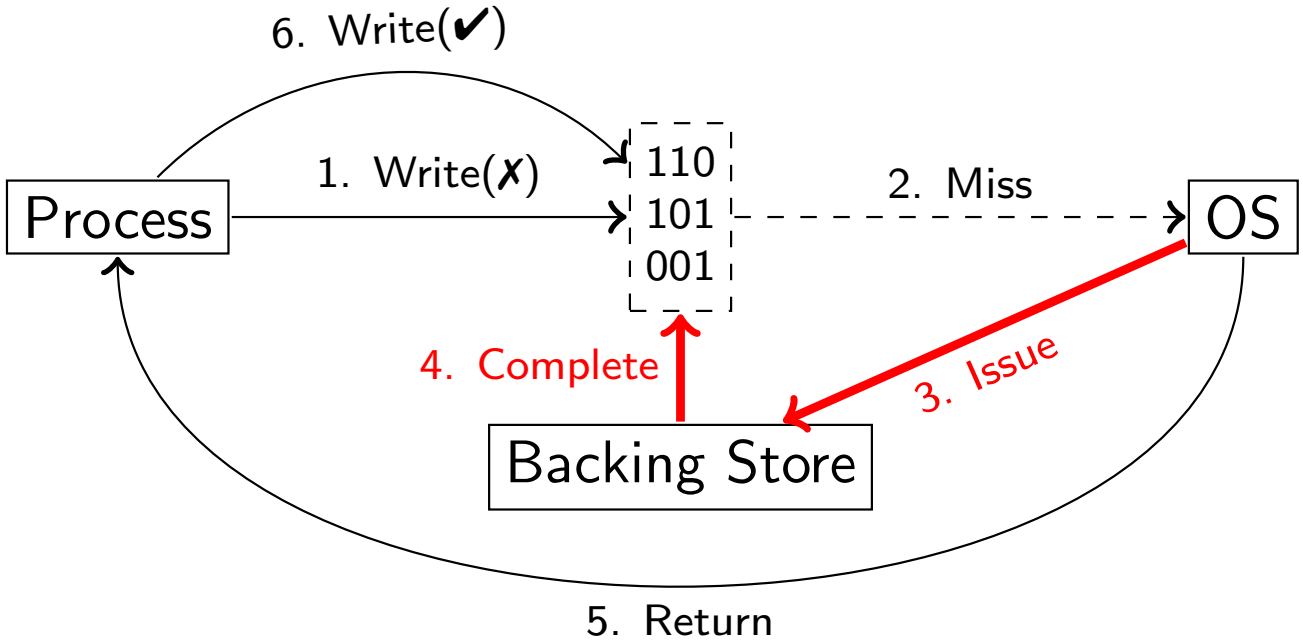

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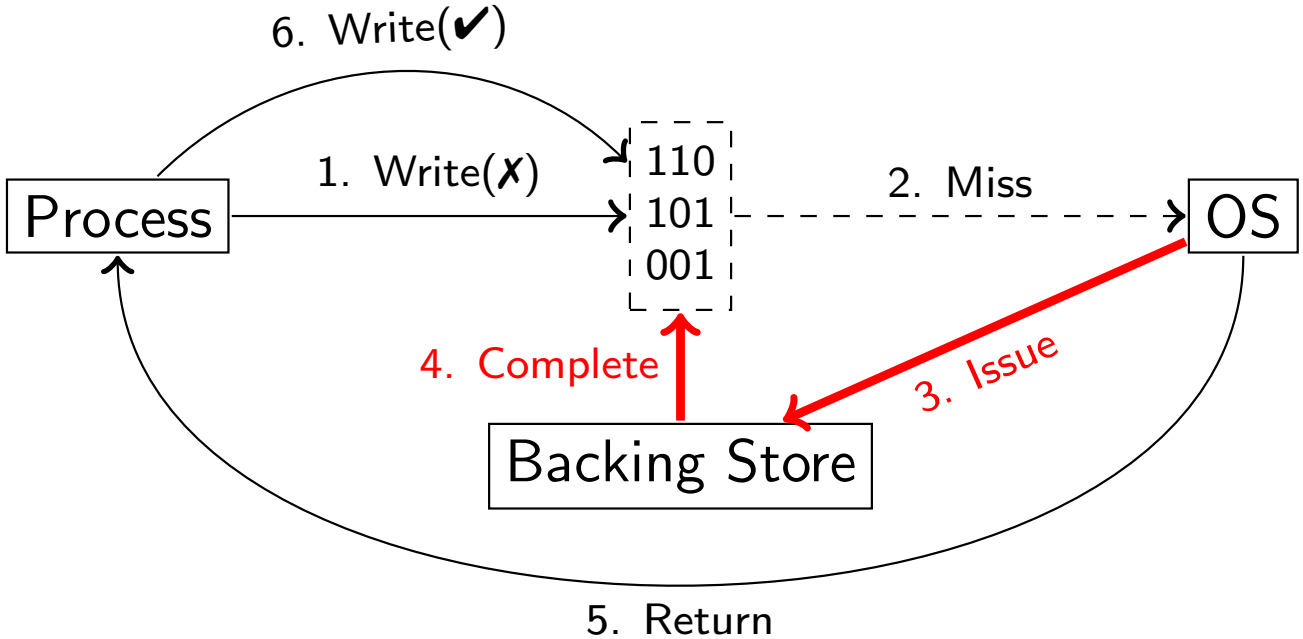

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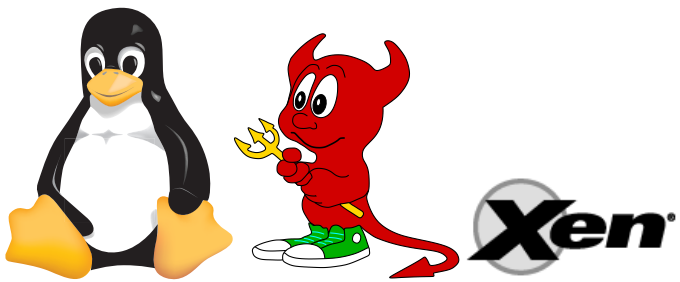

Non-blocking Writes: Basic Approach

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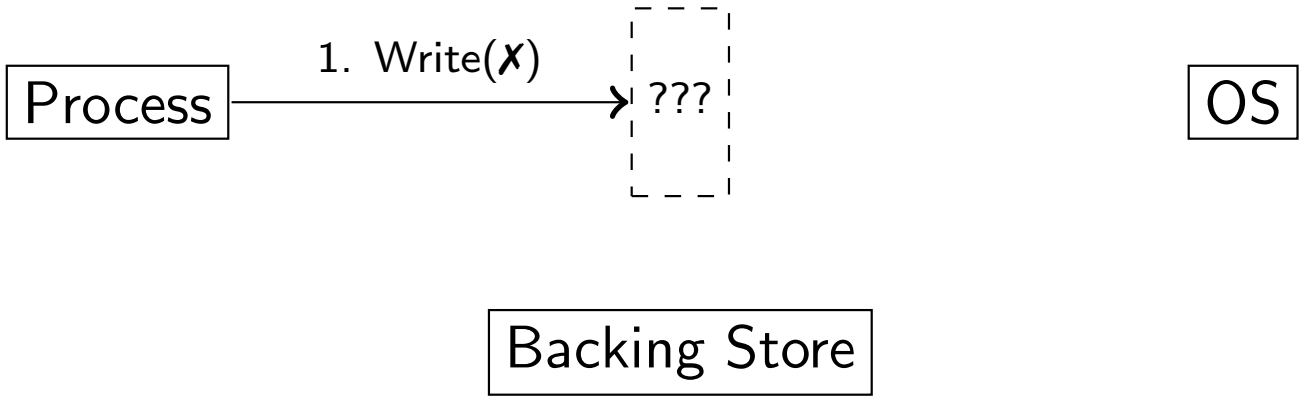

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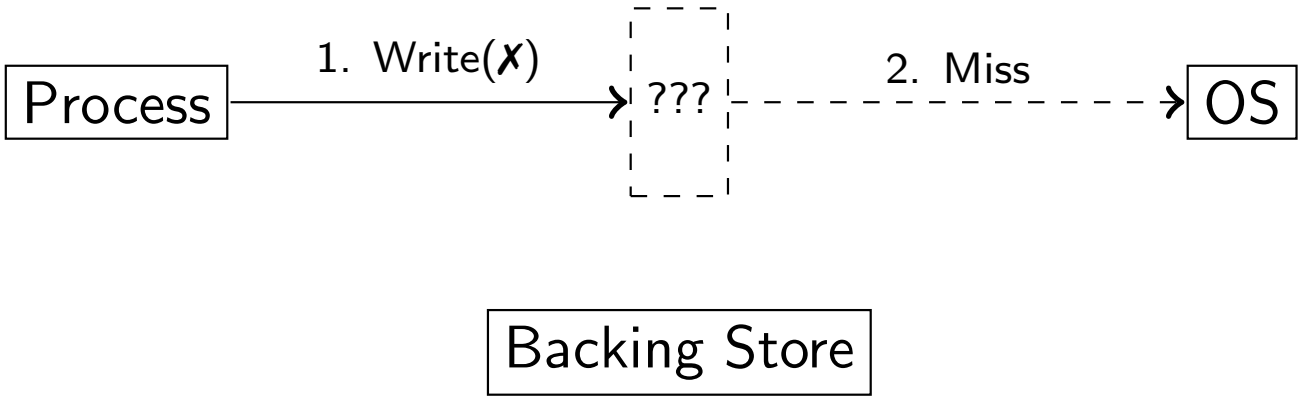

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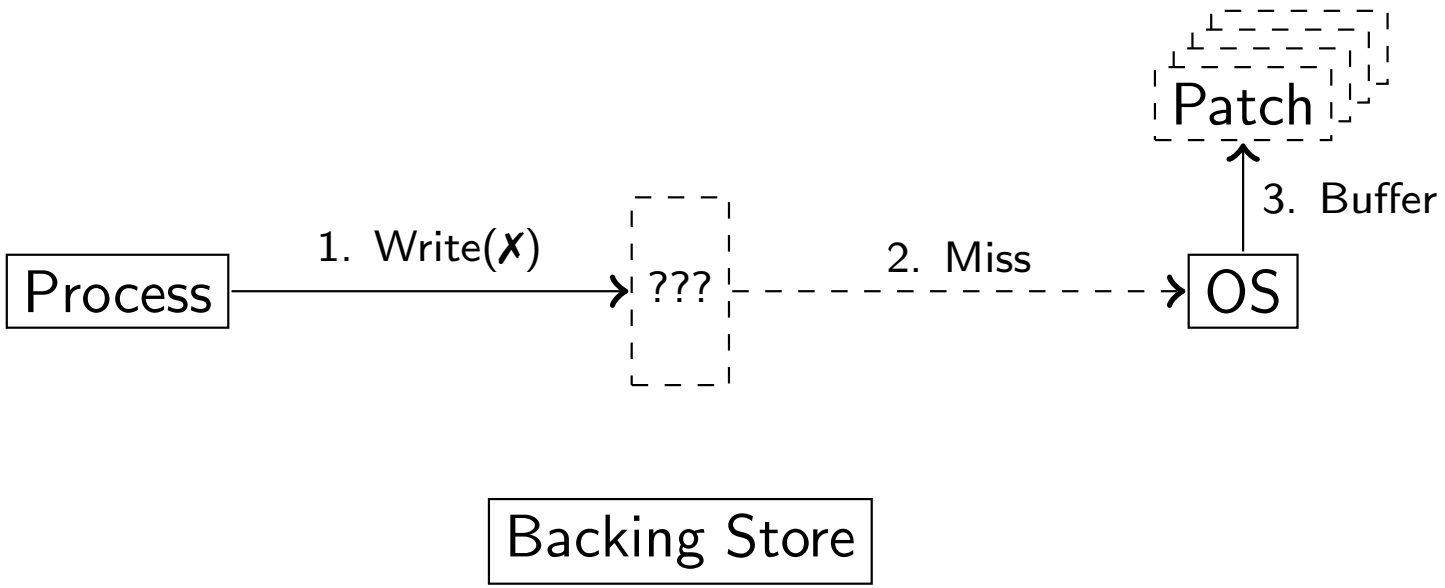

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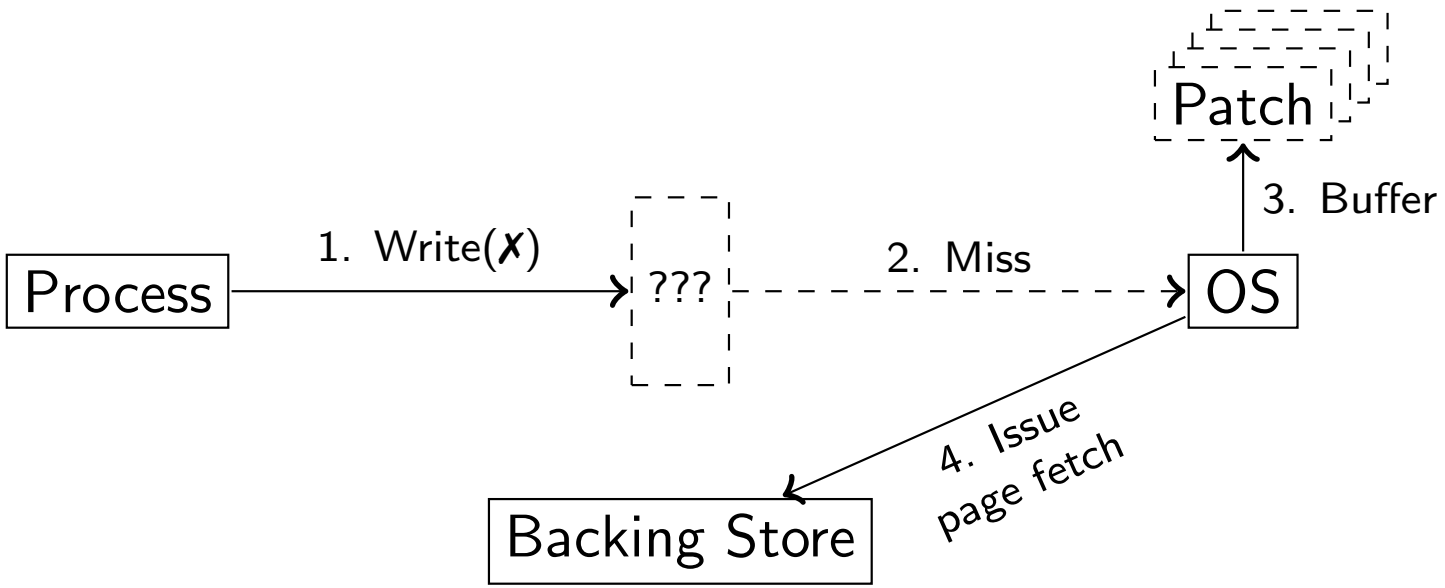

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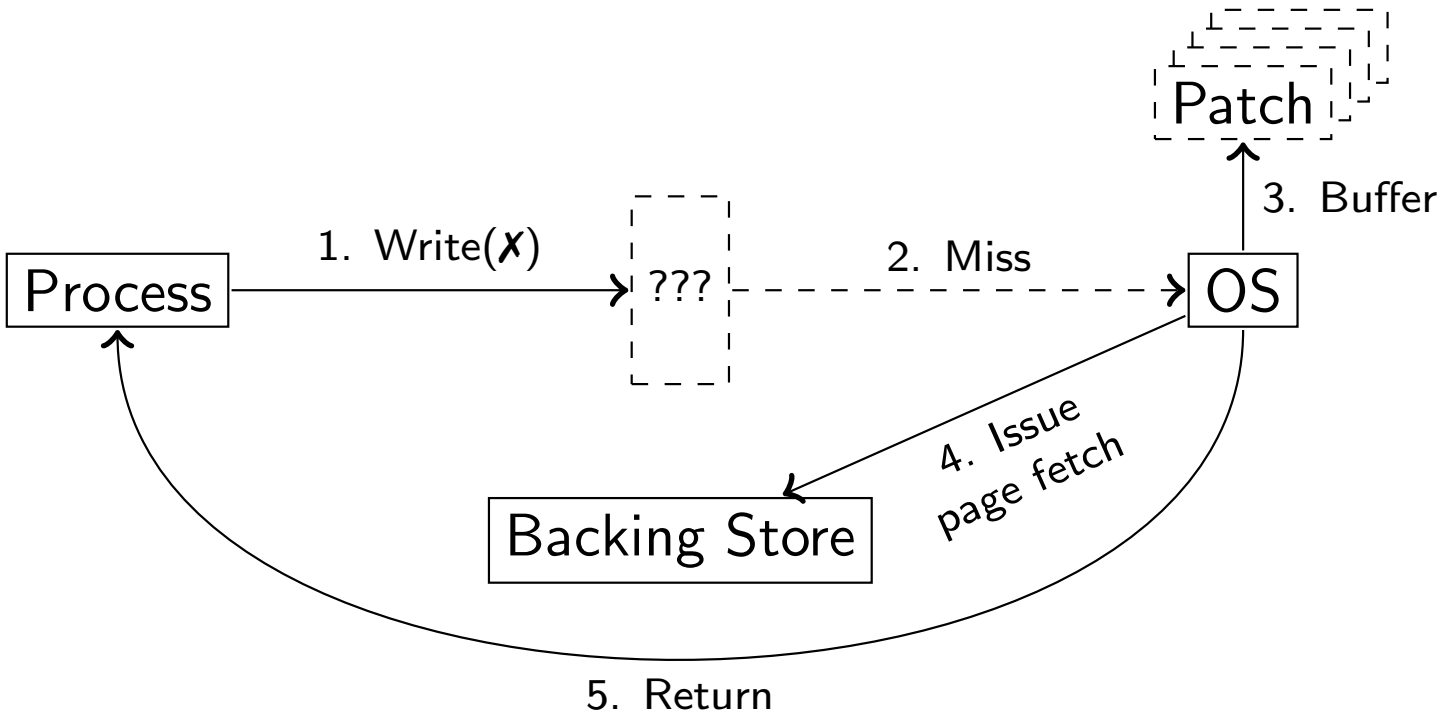

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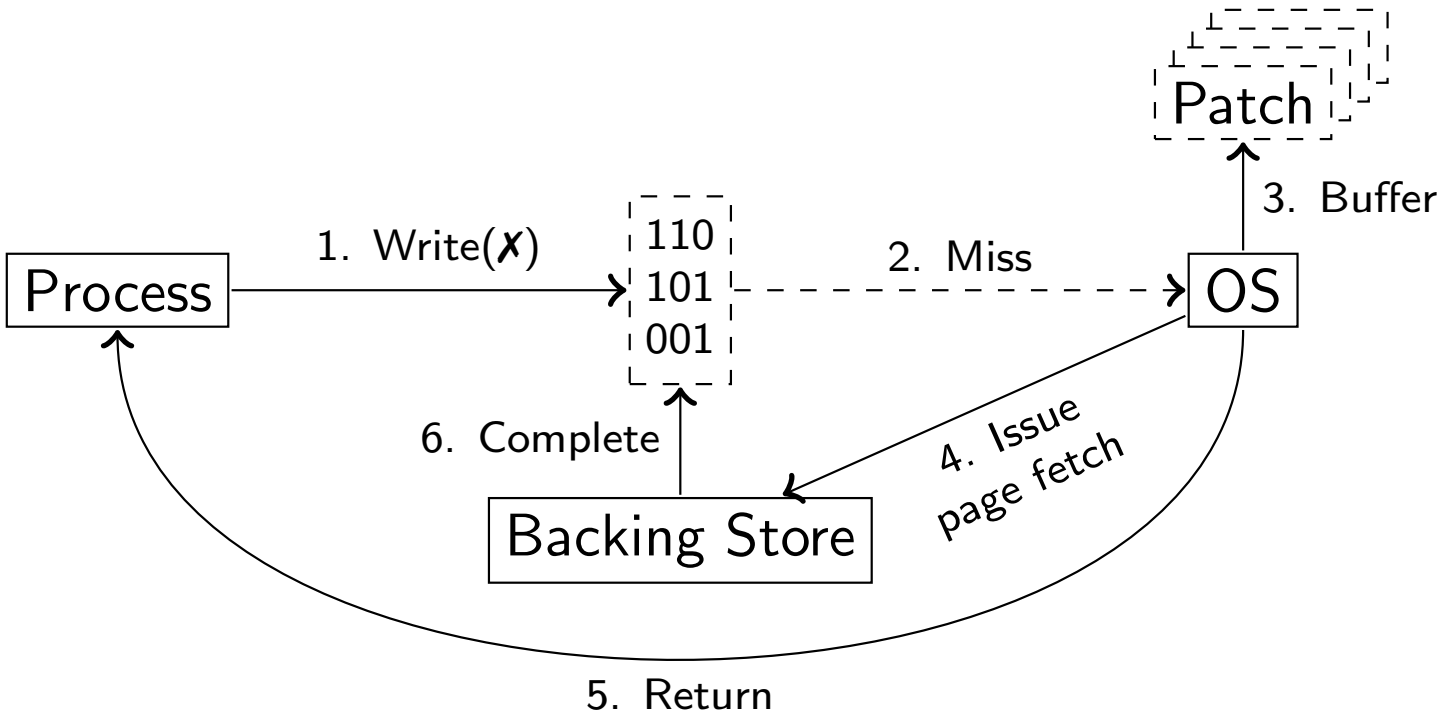

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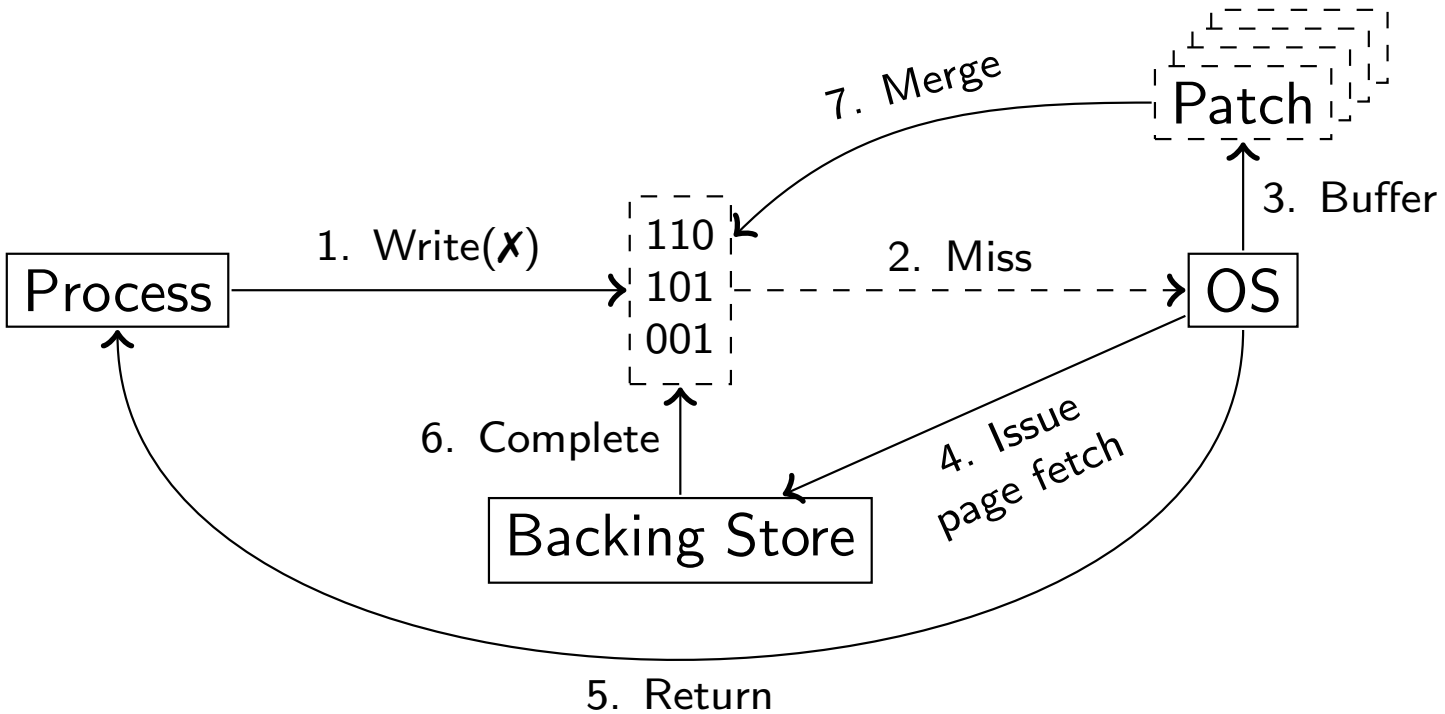

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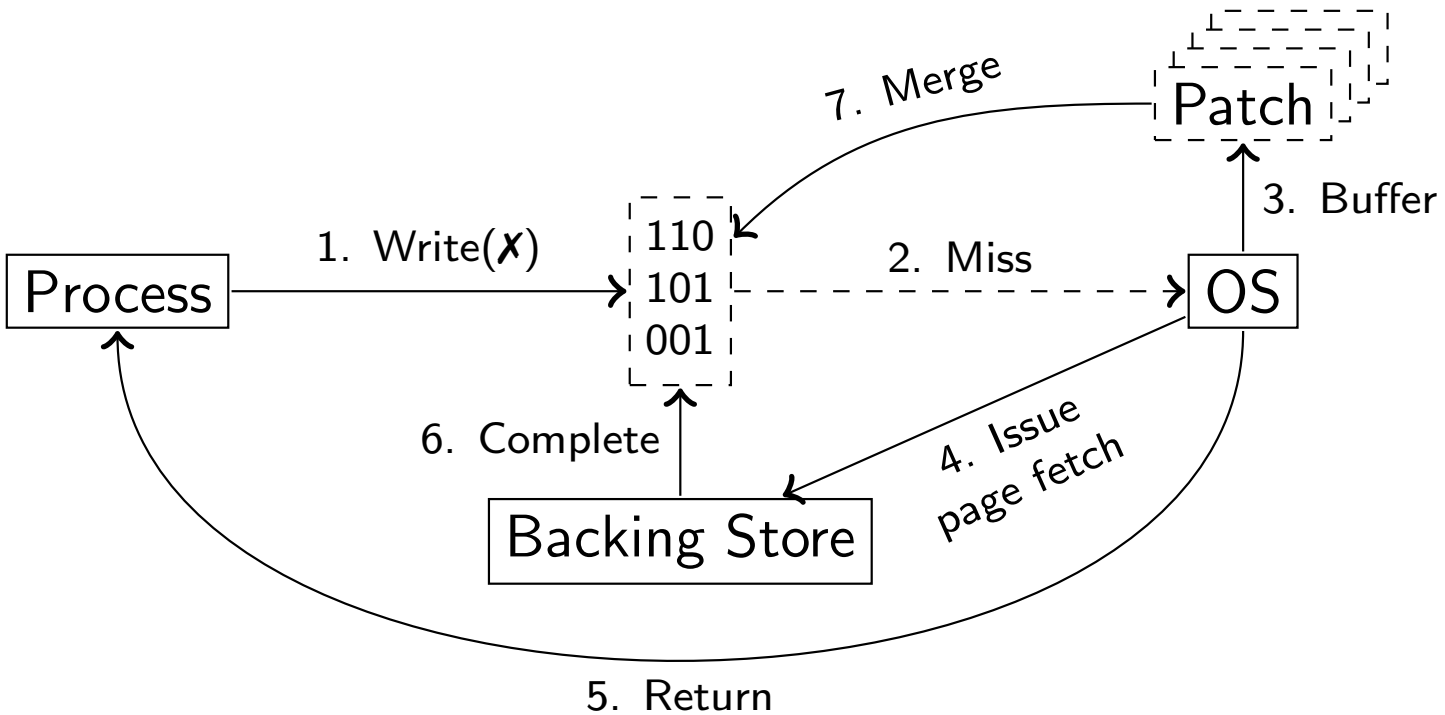
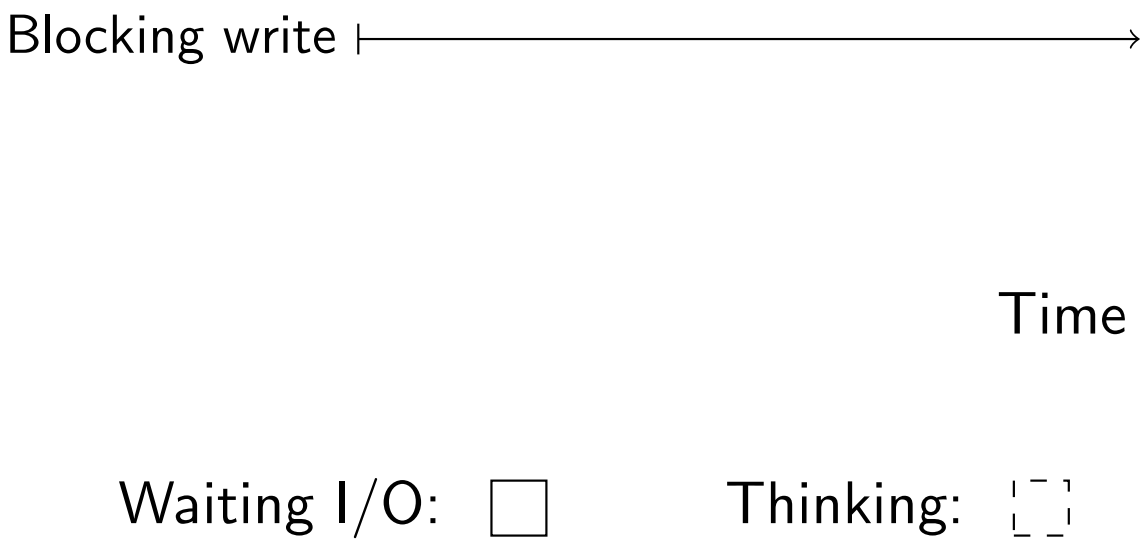


Benefits

1. Reduced access latency to out-of-core pages
2. Increased backing store bandwidth usage

NBW: Page Fetch Asynchrony



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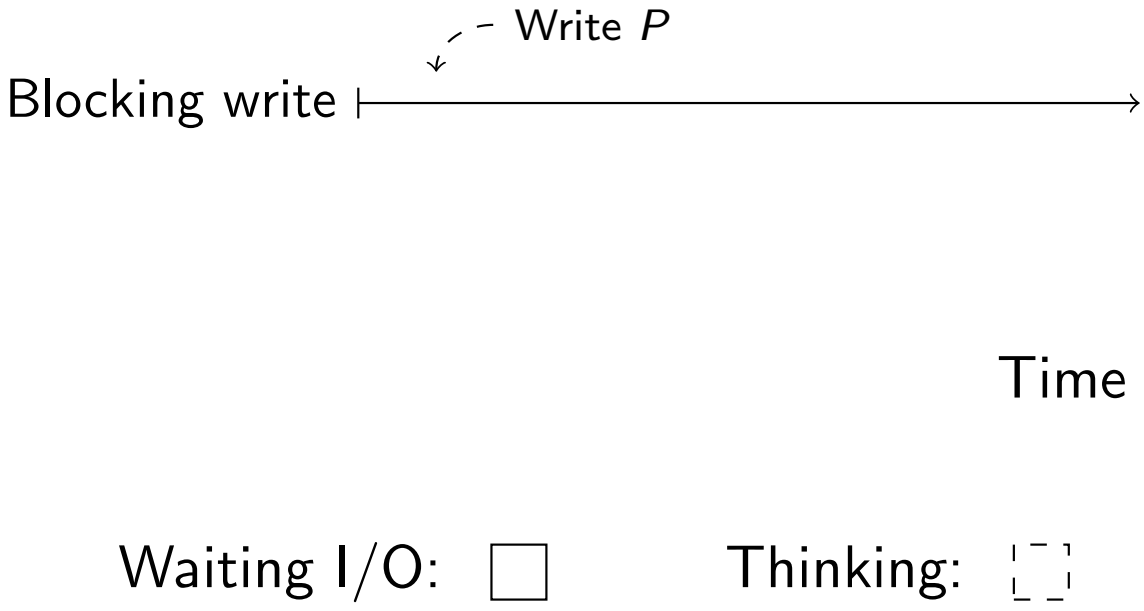

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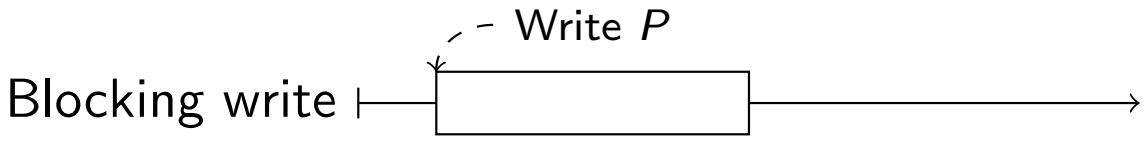
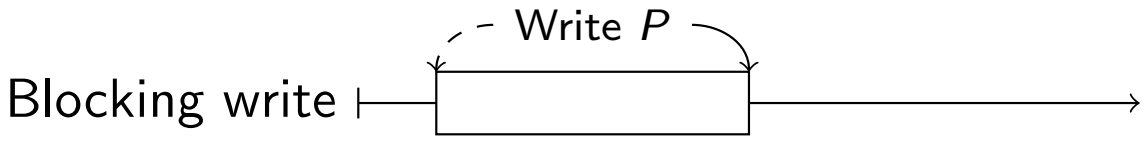


Time

Waiting I/O: 

Thinking: 

NBW: Page Fetch Asynchrony



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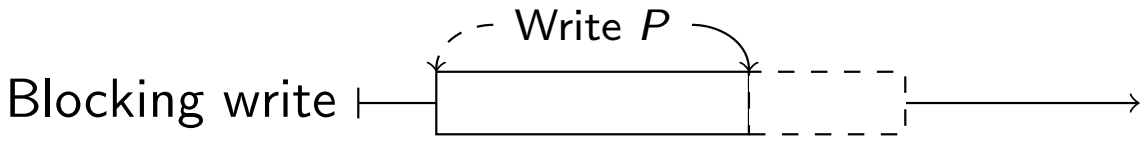

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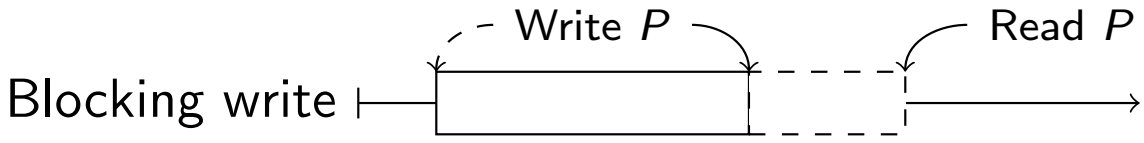
Waiting I/O: ☐ Thinking: ⬚

NBW: Page Fetch Asynchrony



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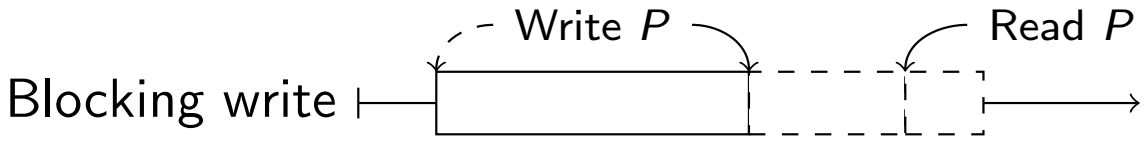

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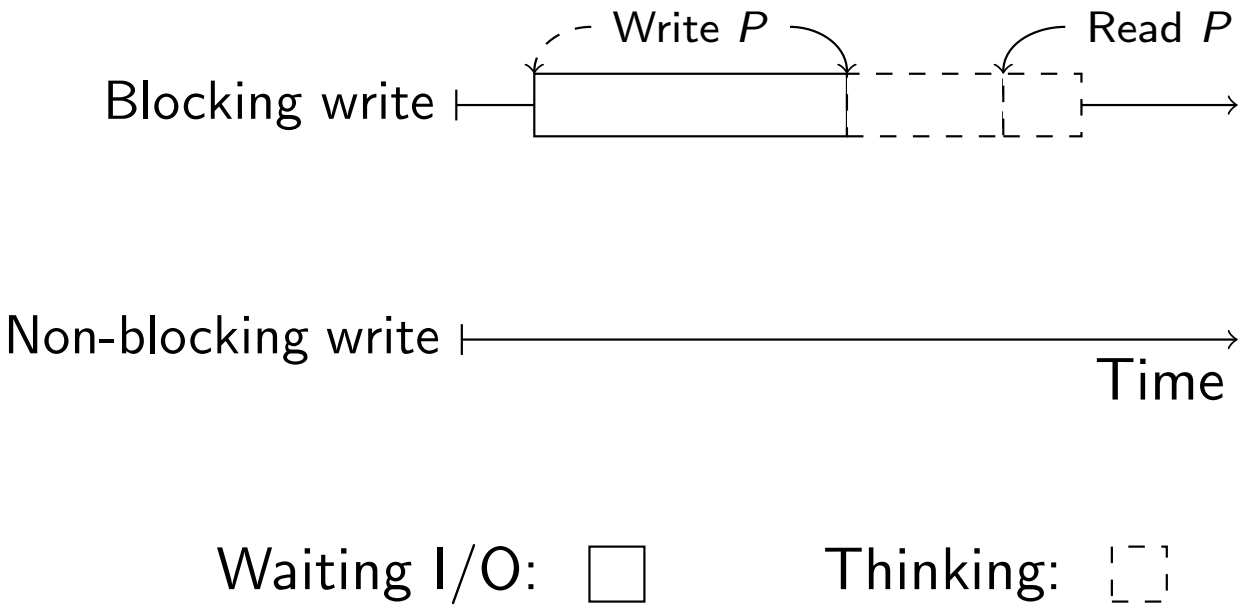

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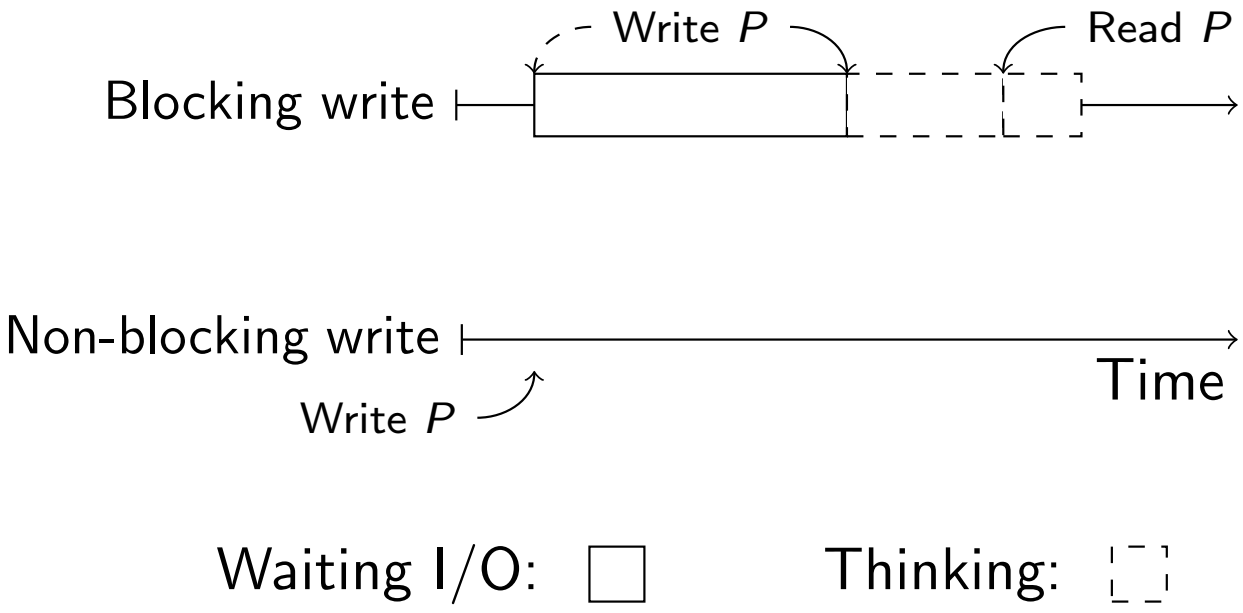

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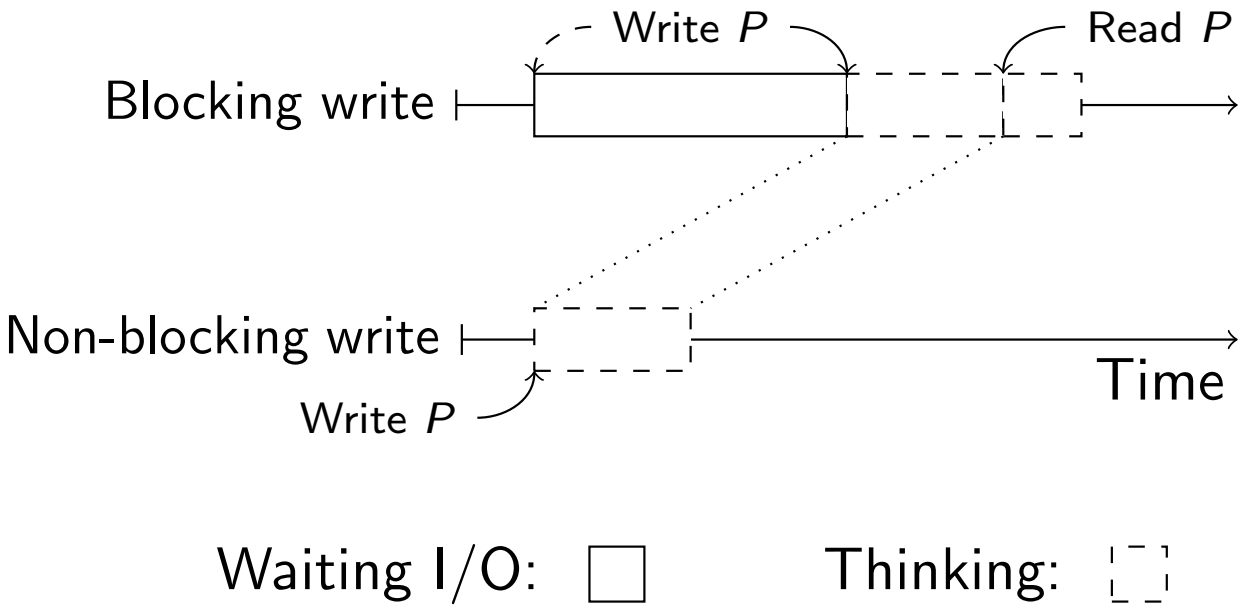

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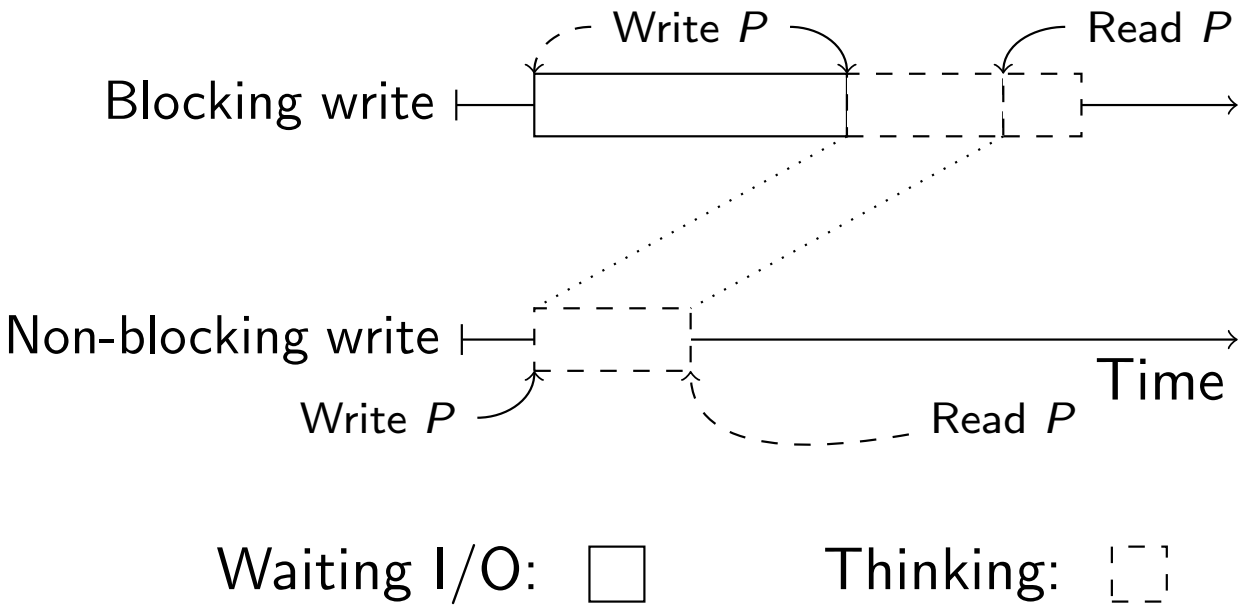

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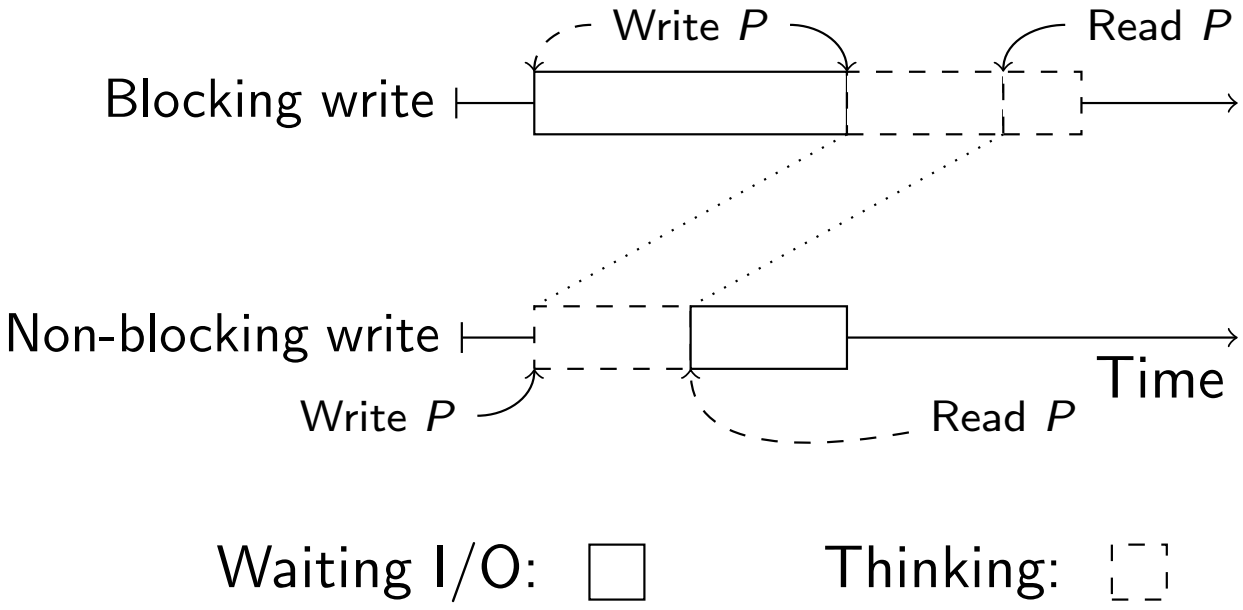

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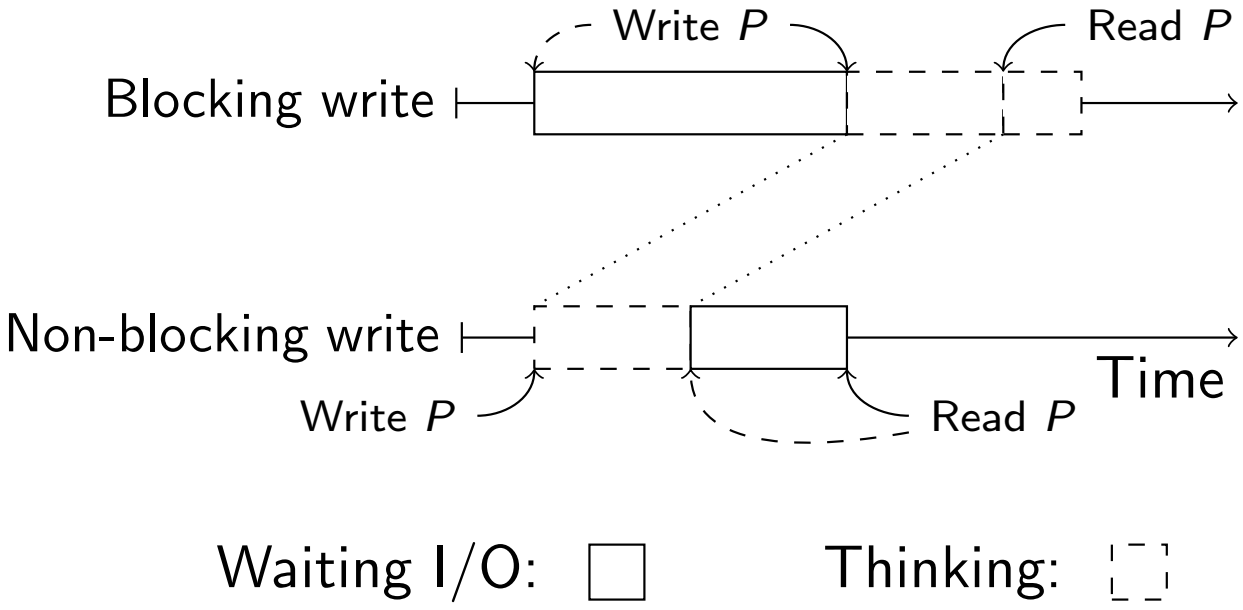

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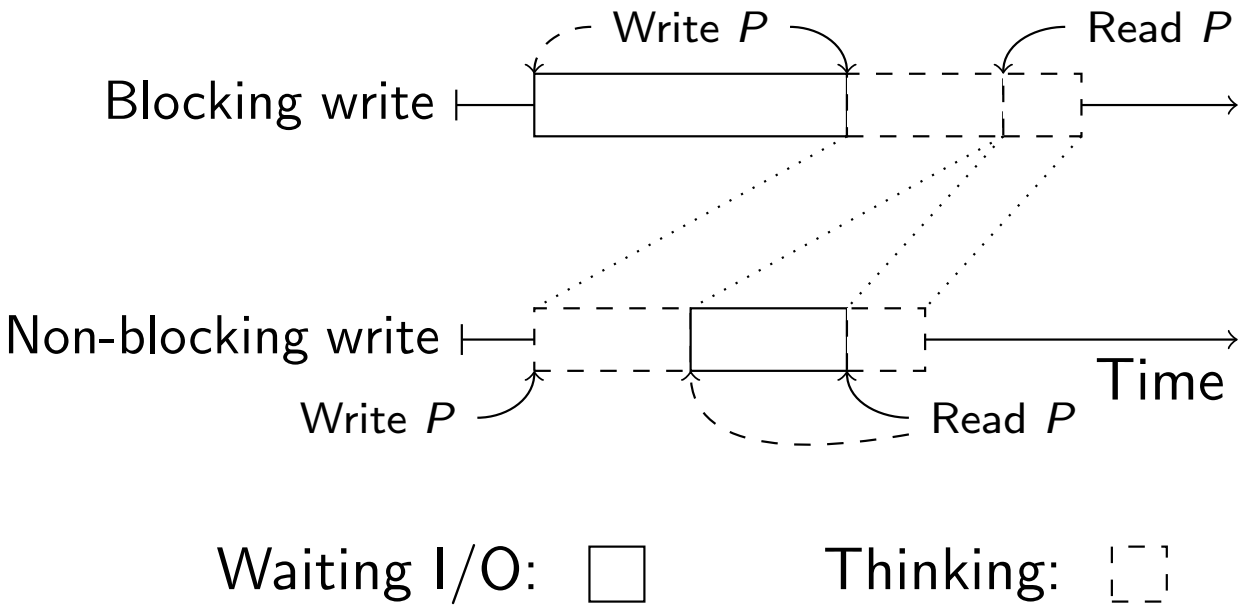

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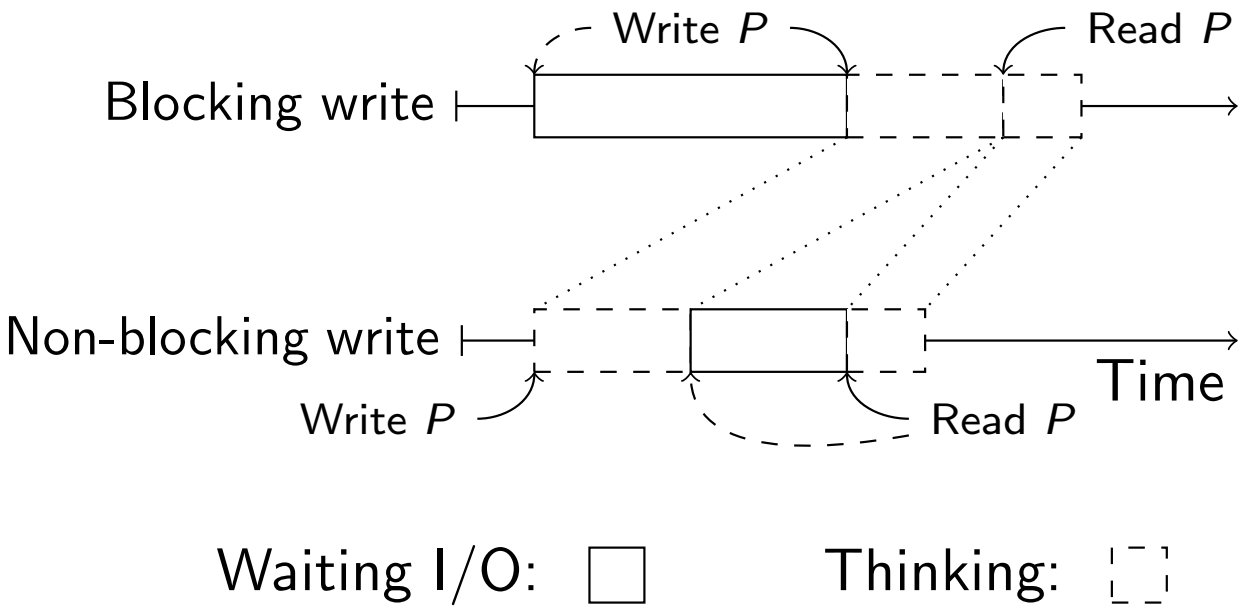
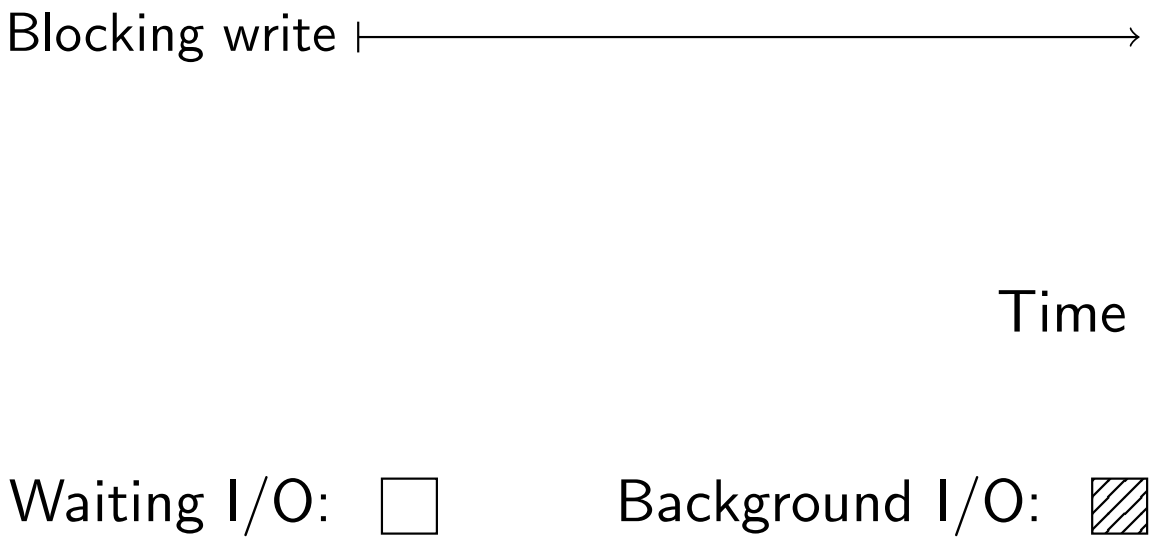


- Immediate return from write
- Overlaping of I/O and computation

NBW: Page Fetch Parallelism



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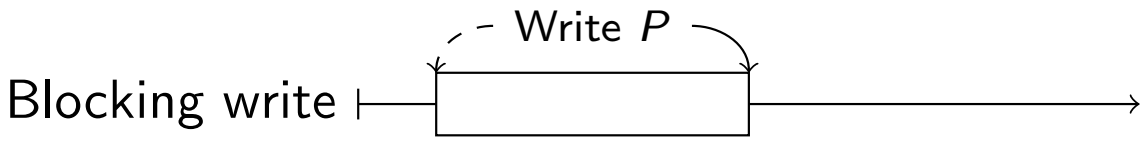
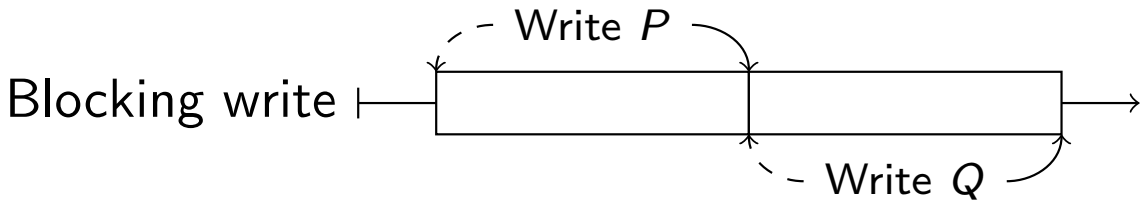


Time

Waiting I/O: 

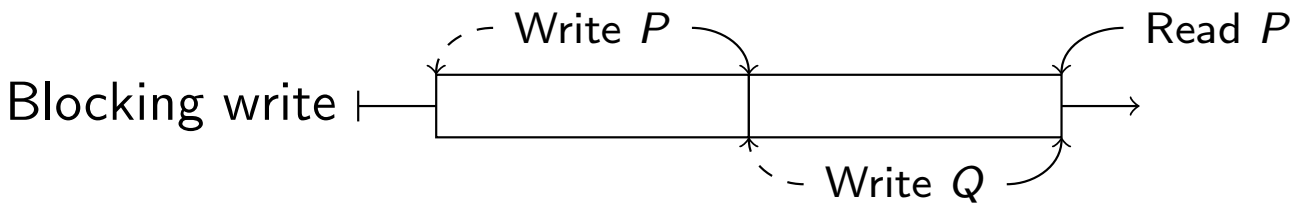
Background I/O: 

NBW: Page Fetch Parallelism



Waiting I/O: ☐ Background I/O: ▨

NBW: Page Fetch Parallelism



Time

Waiting I/O: ☐ Background I/O: ▨

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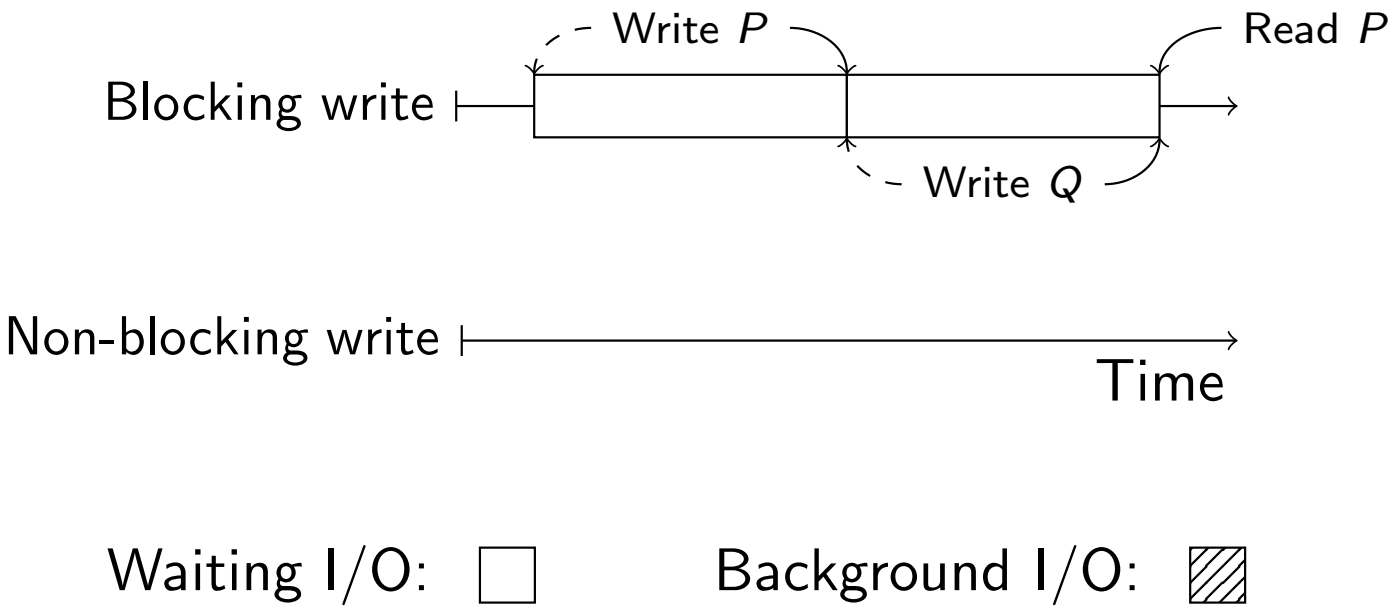

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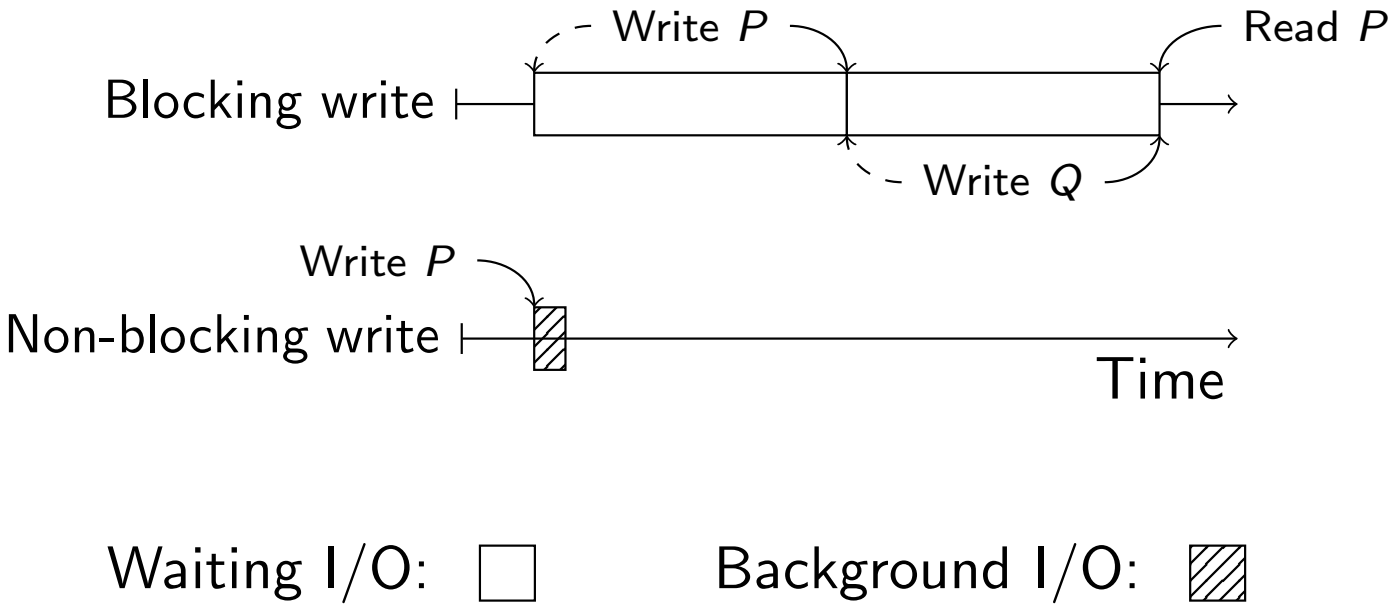

Waiting I/O: ☐ Background I/O: ▨

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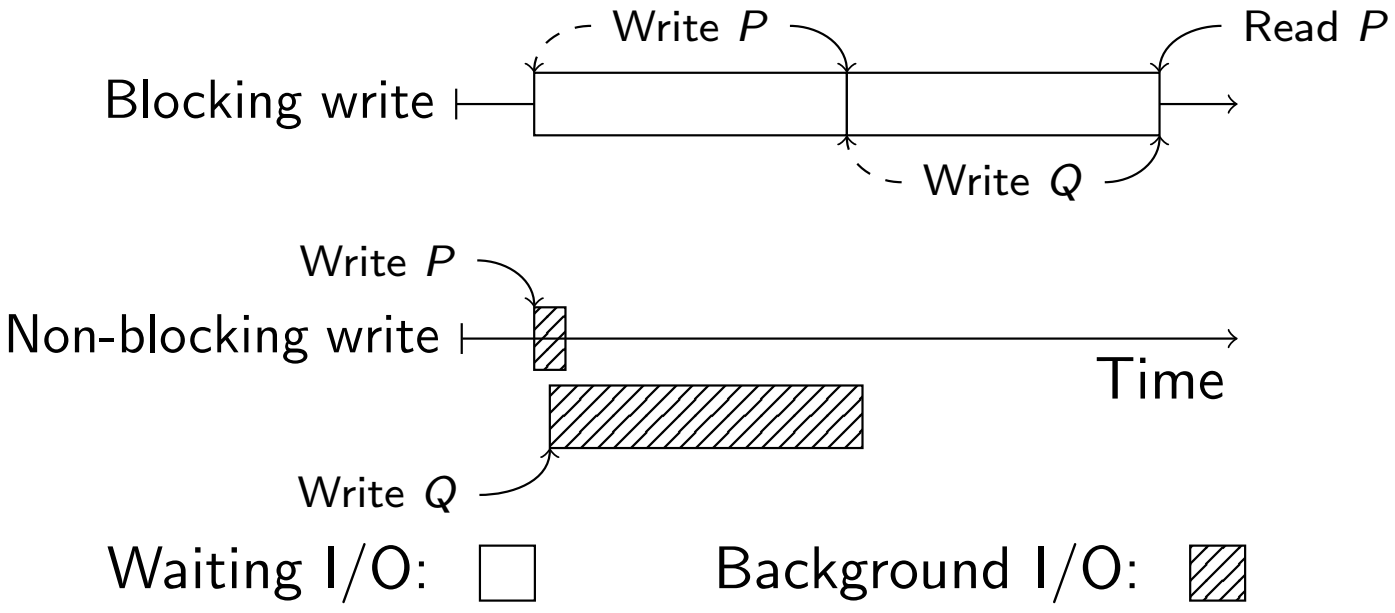

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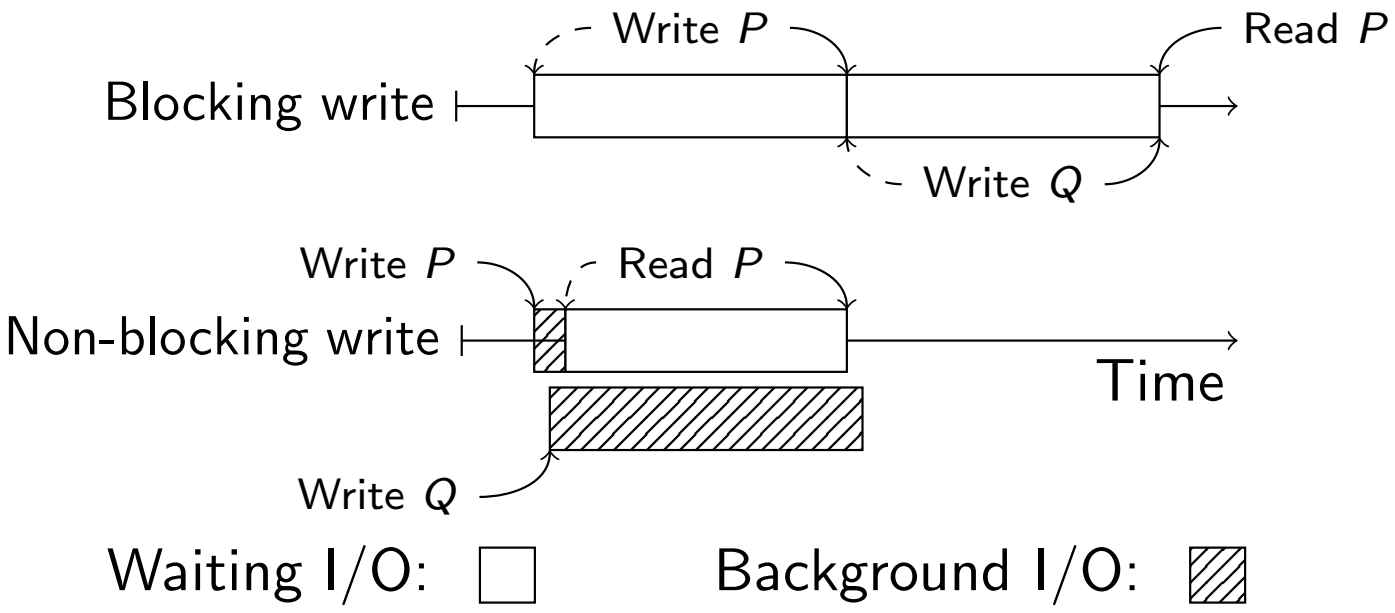

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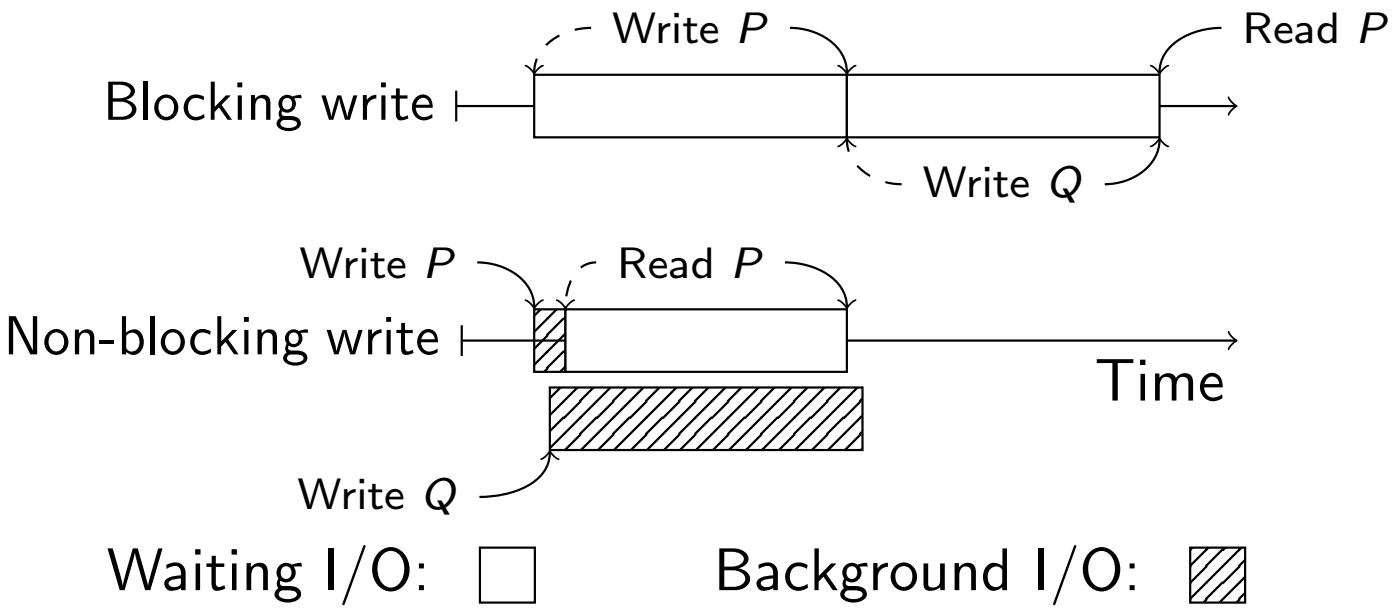

- Increases I/O parallelism
- Increases I/O scheduler efficiency

Delaying Page Fetches

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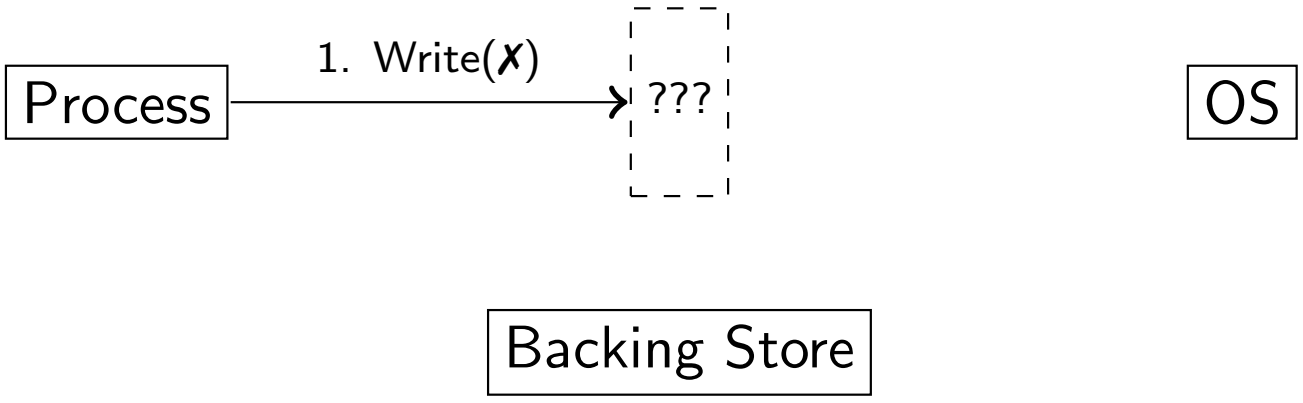

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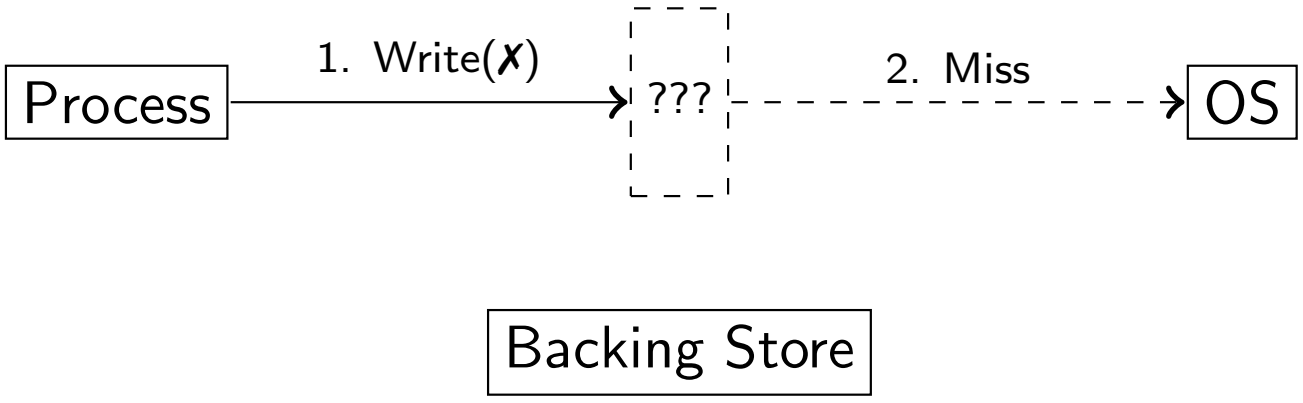

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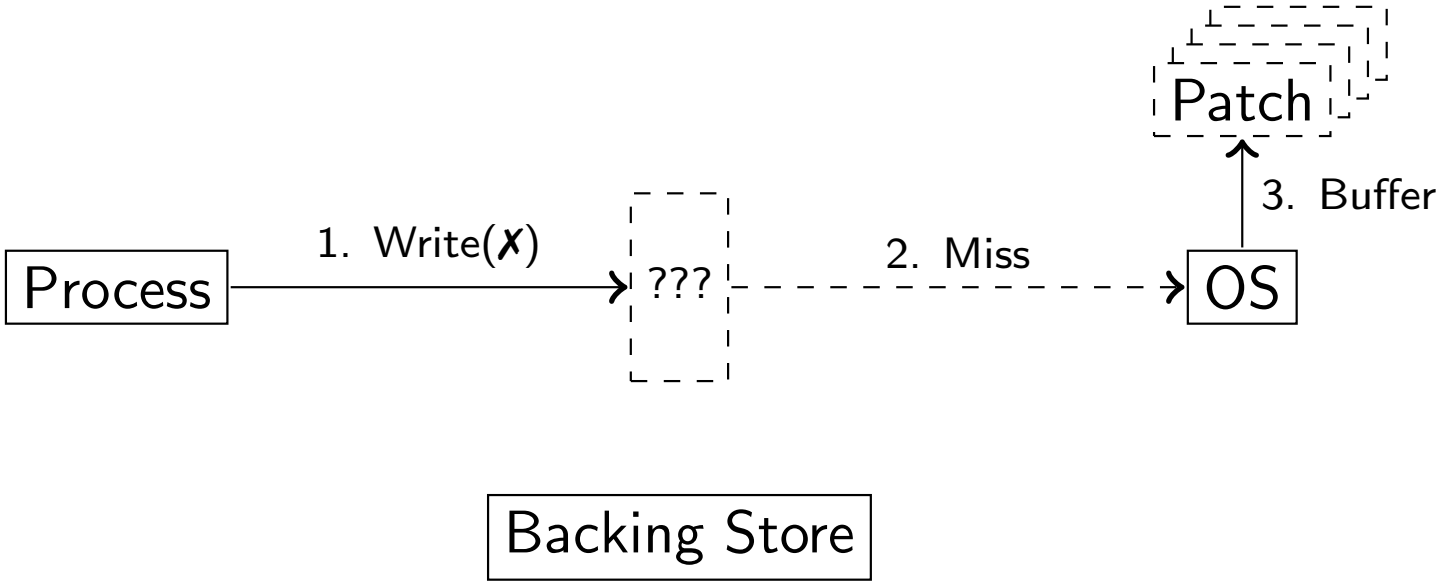

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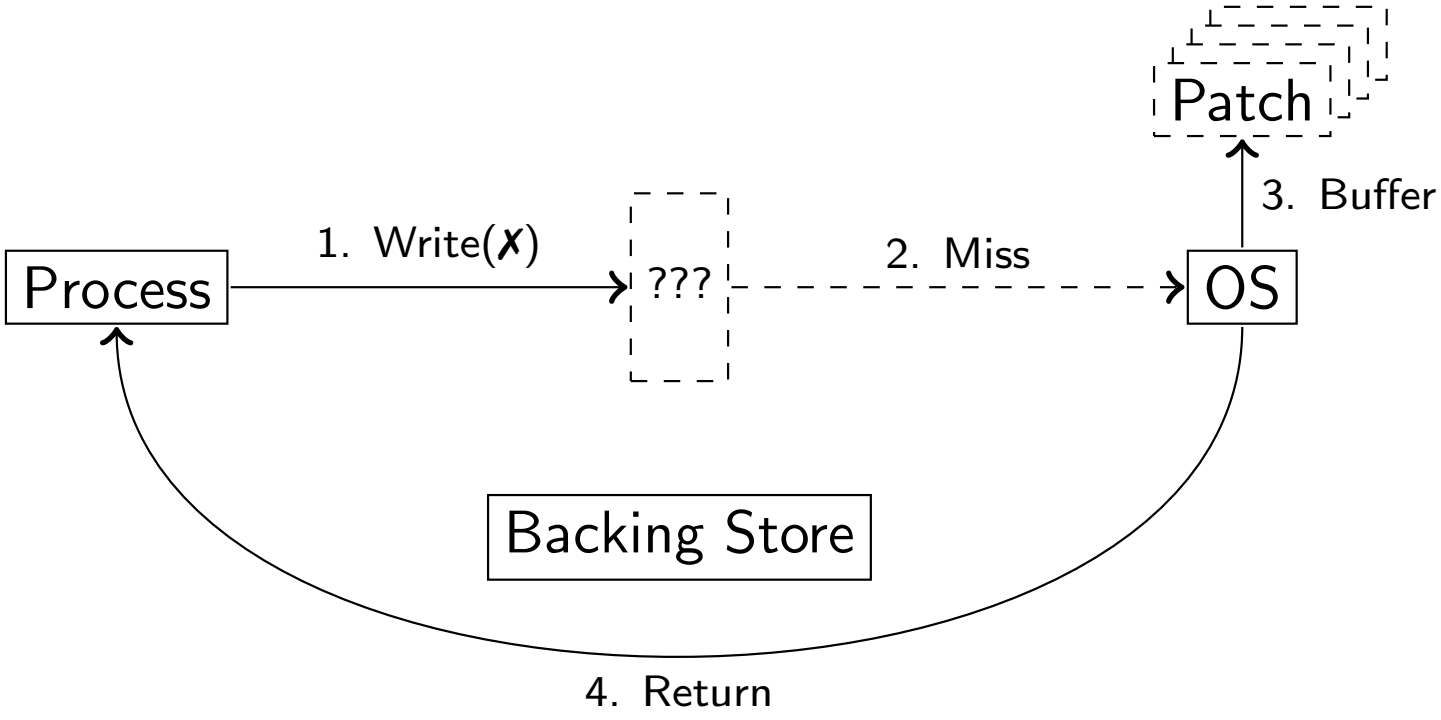

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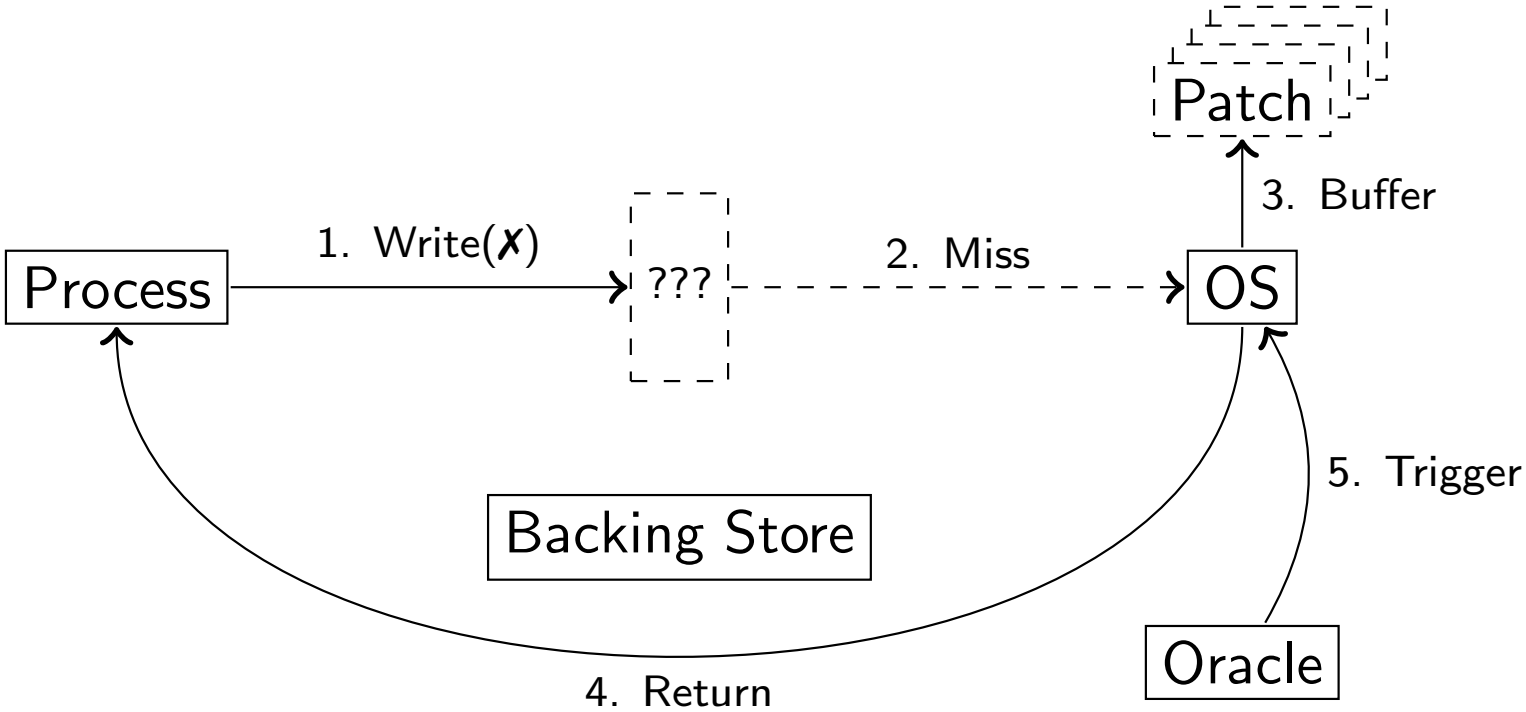

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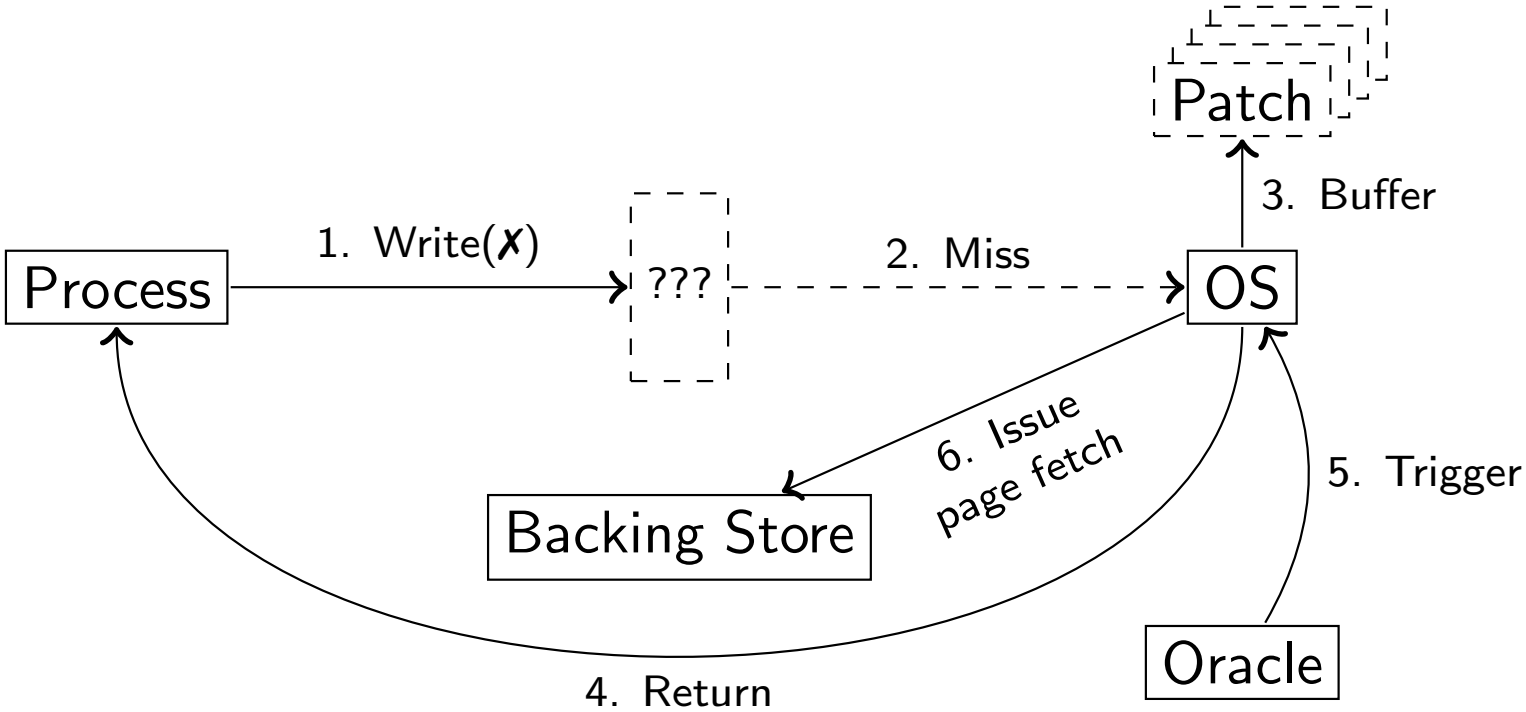

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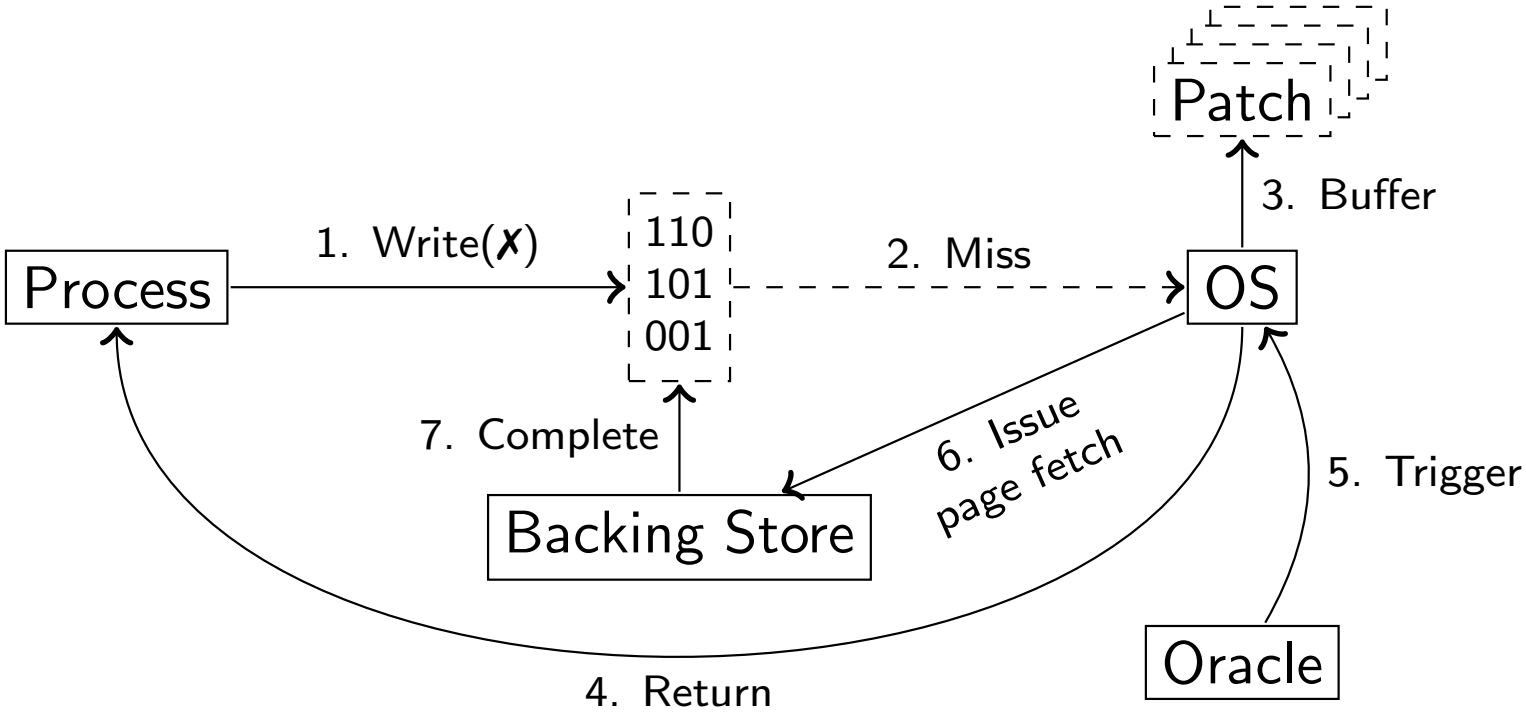

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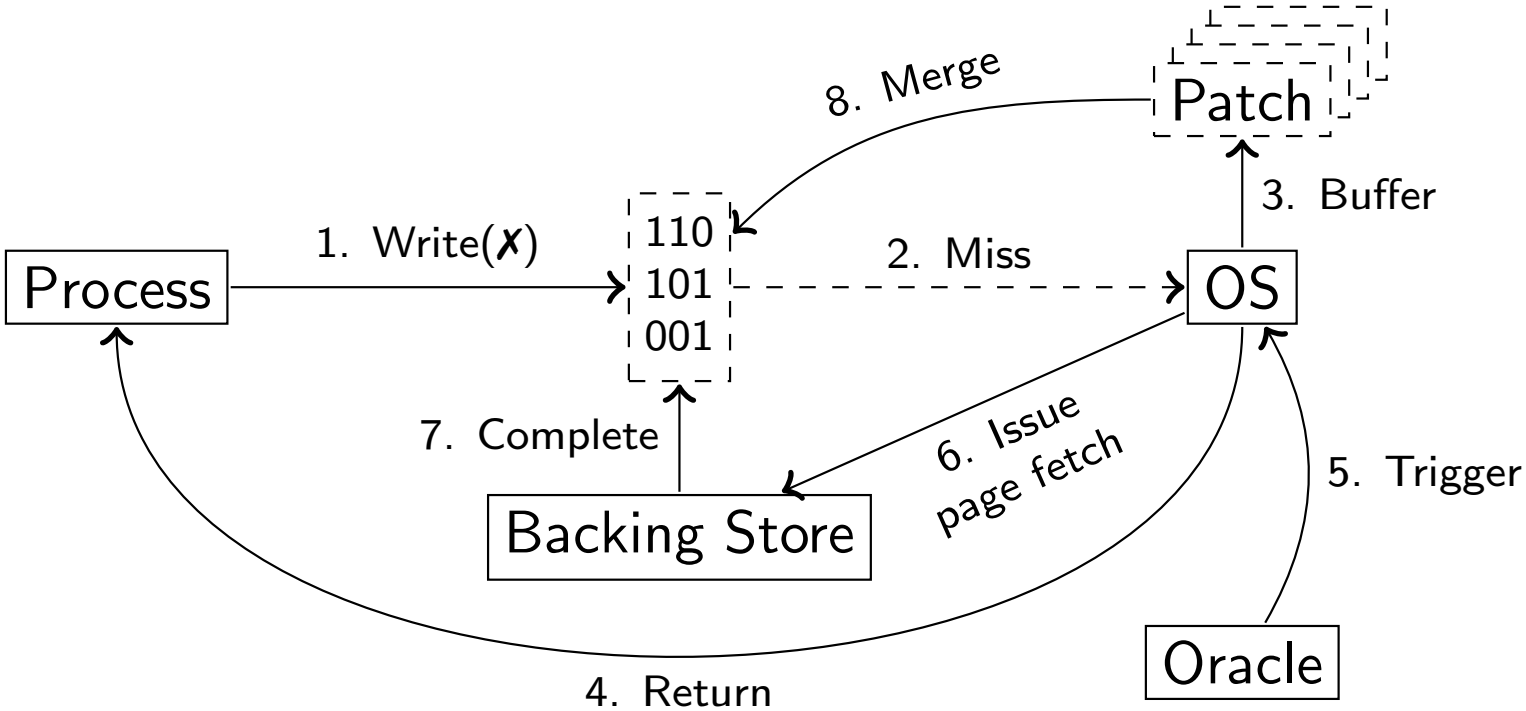

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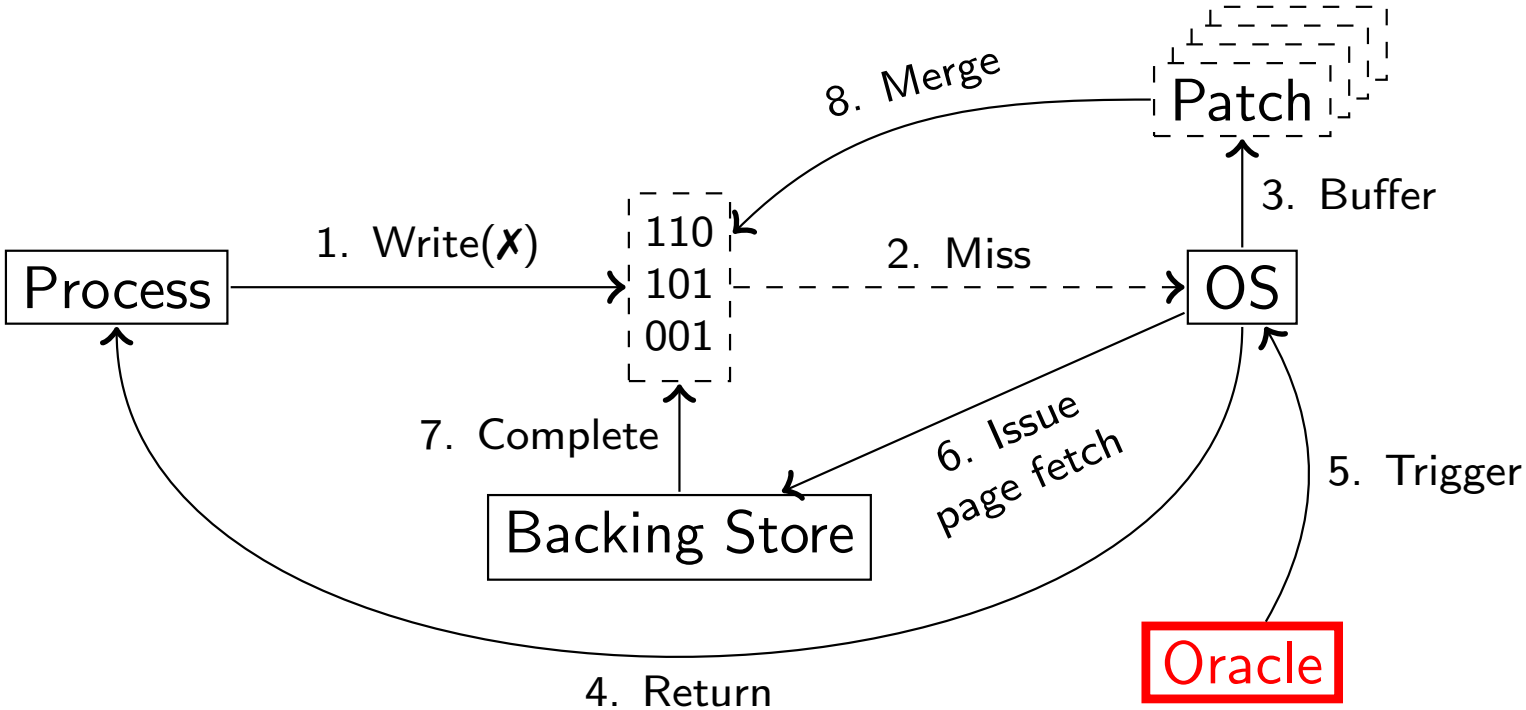

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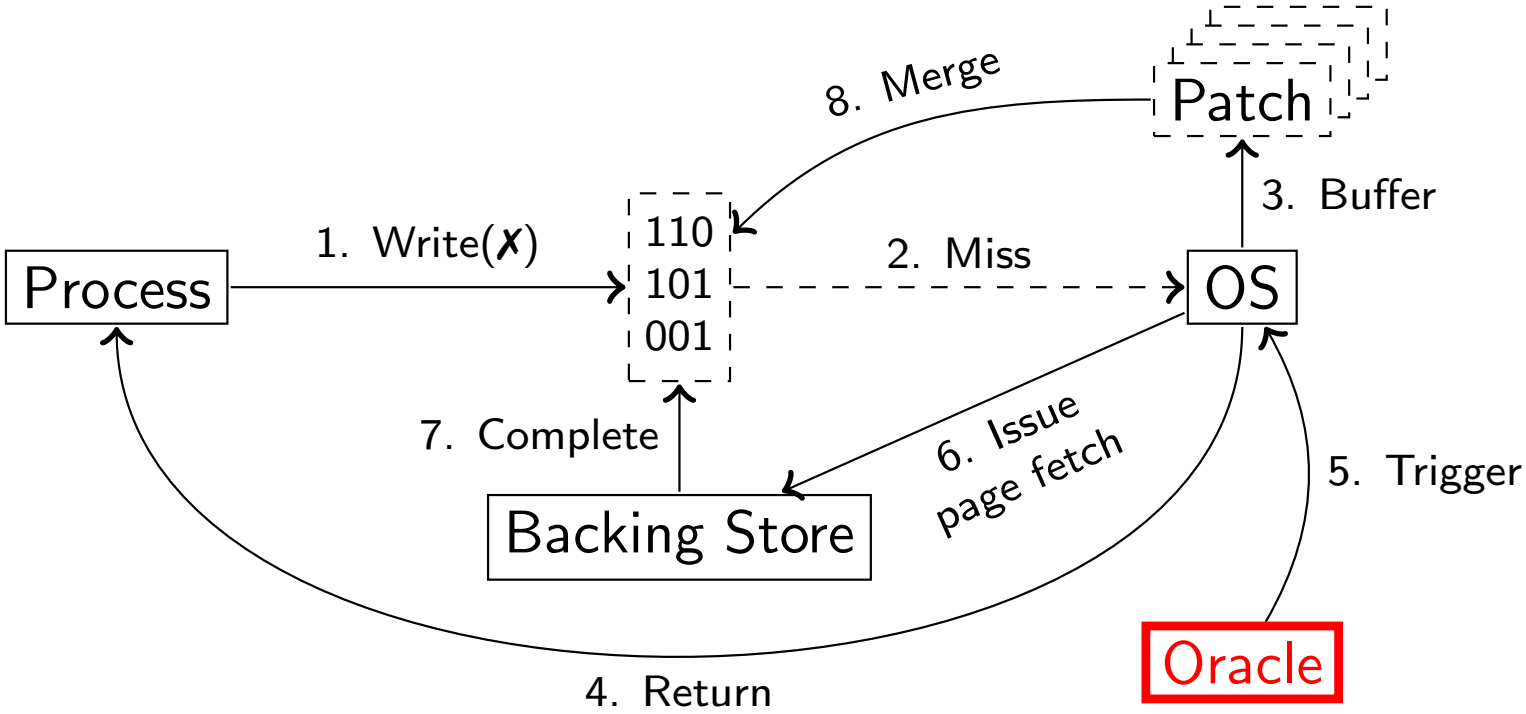

Oracle Uses

1. Save power by delaying fetches until disks spin-up (EXCES & SRCMap)
2. Help systems under resource pressure: Disk or Memory
3. Reduce memory usage by delaying page allocation

Patch Optimizations

Read

We can read data from patches

- Making reads to out-of-core pages also asynchronous
- Delay fetch further if required

Merge

Merge a new patch with an old one and build a new bigger patch

- Reduce meta-data

Re-use

If re-writing a patch, re-use the old one

- Reduce meta-data
- Reduce patch queue size

NBW Evaluation

- We implemented NBW for Linux for x86
- All patch optimizations implemented
- We only evaluate *asynchronous* mode for performance
- We use 10 workloads:
  - ✓ 4 SPEC CPU2006 (single-threaded)
  - ✓ 4 DaCapo (multi-threaded)
  - ✓ SPEC SFS file server
  - ✓ SPEC Power application server

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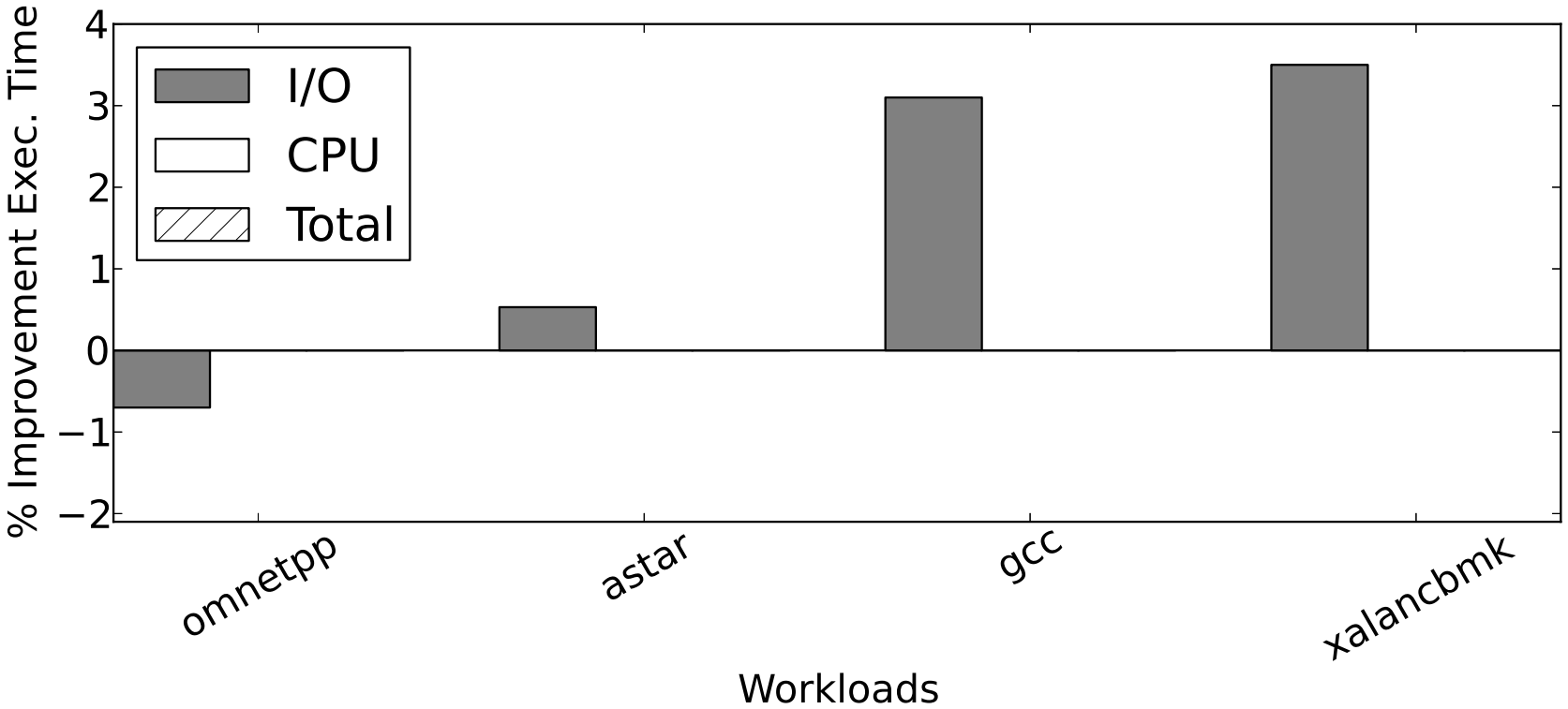

- Average of 5 runs (<2% COV)

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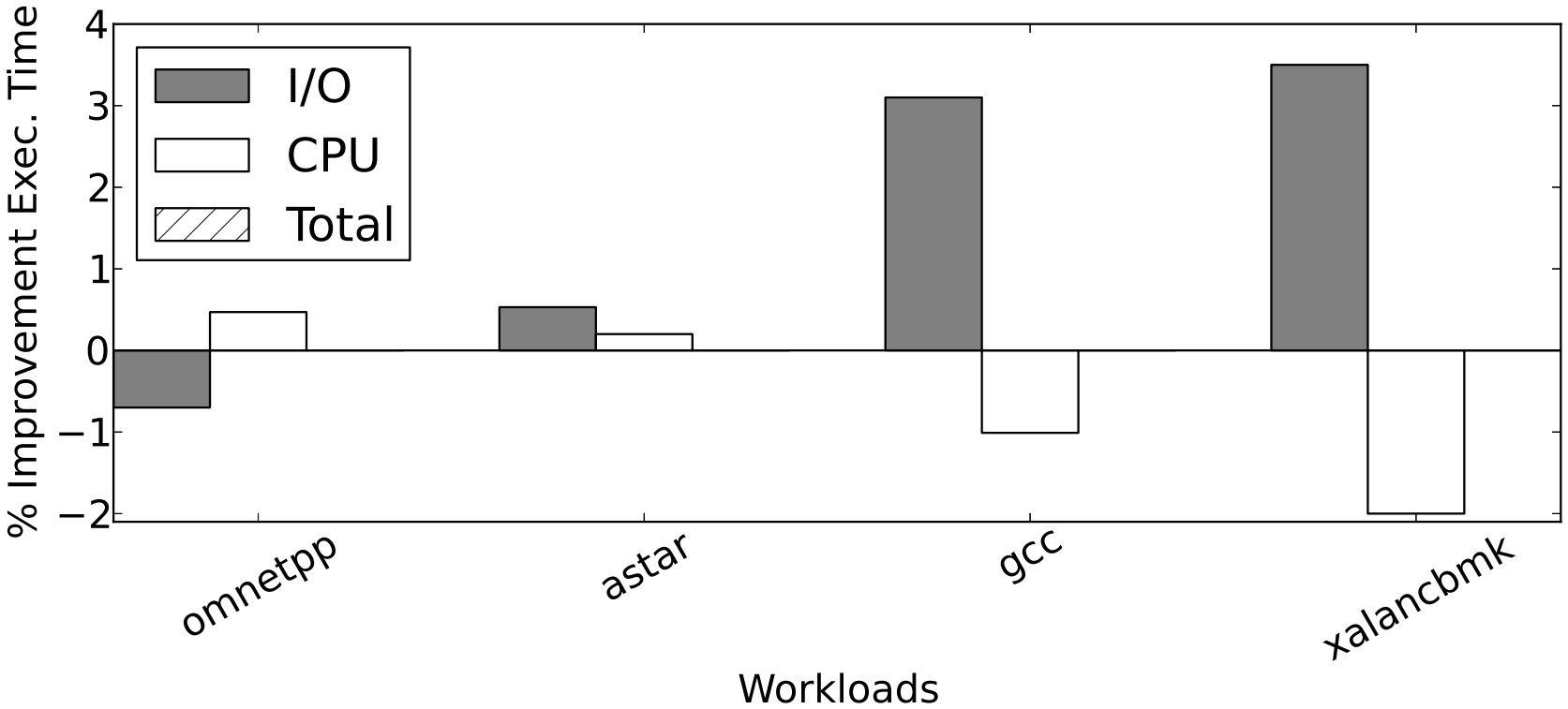

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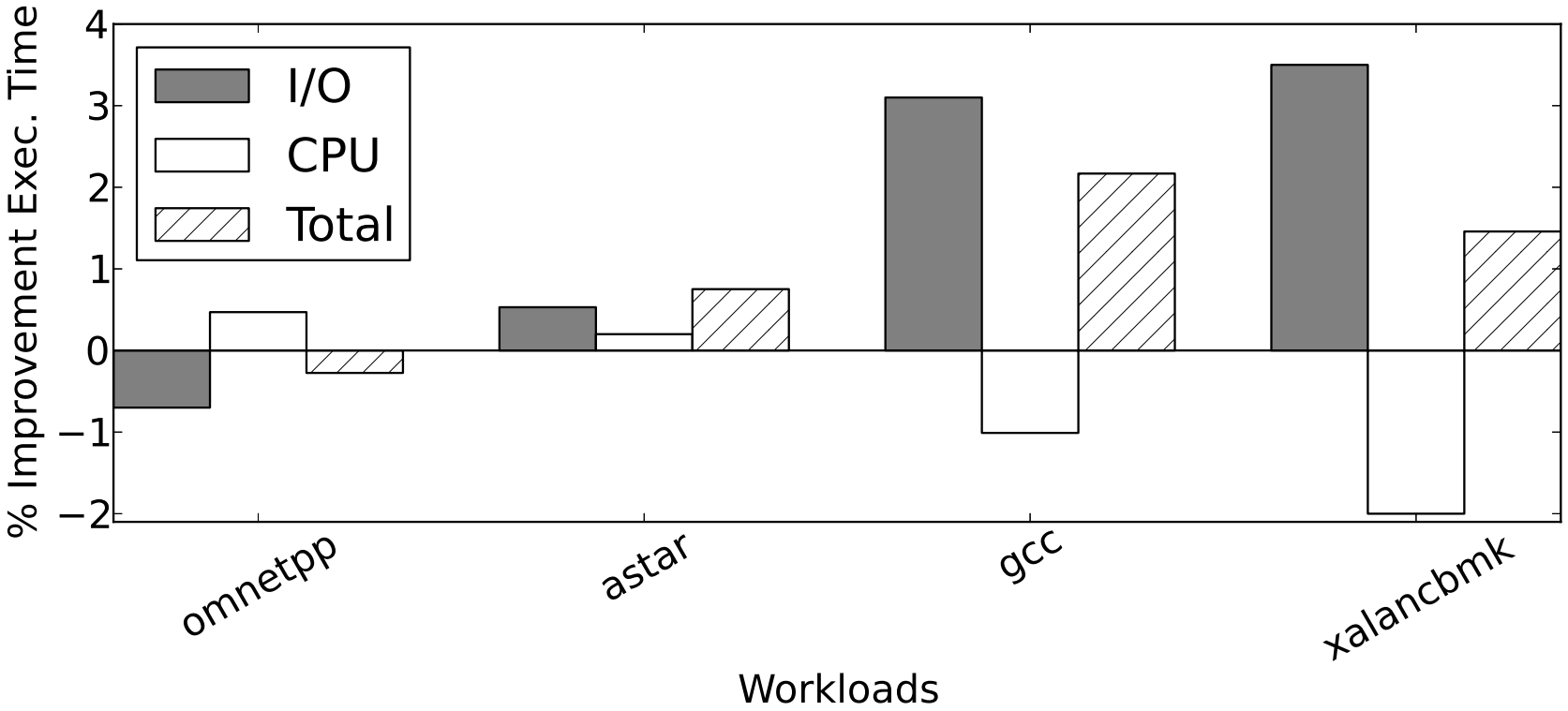

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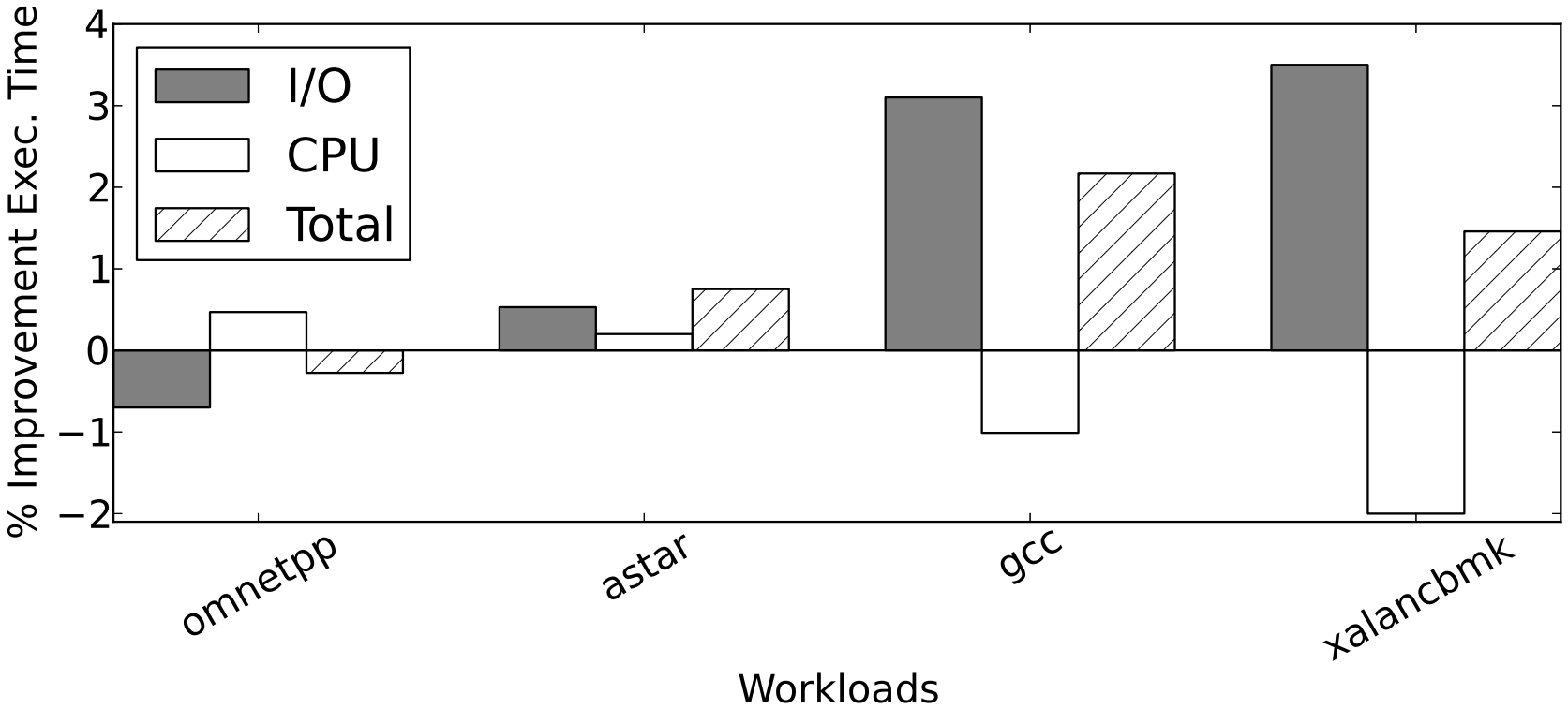

- Average of 5 runs (<2% COV)
- 2.1% gains, higher when memory is reduced
- Memory overhead usually $< 0.1\%$

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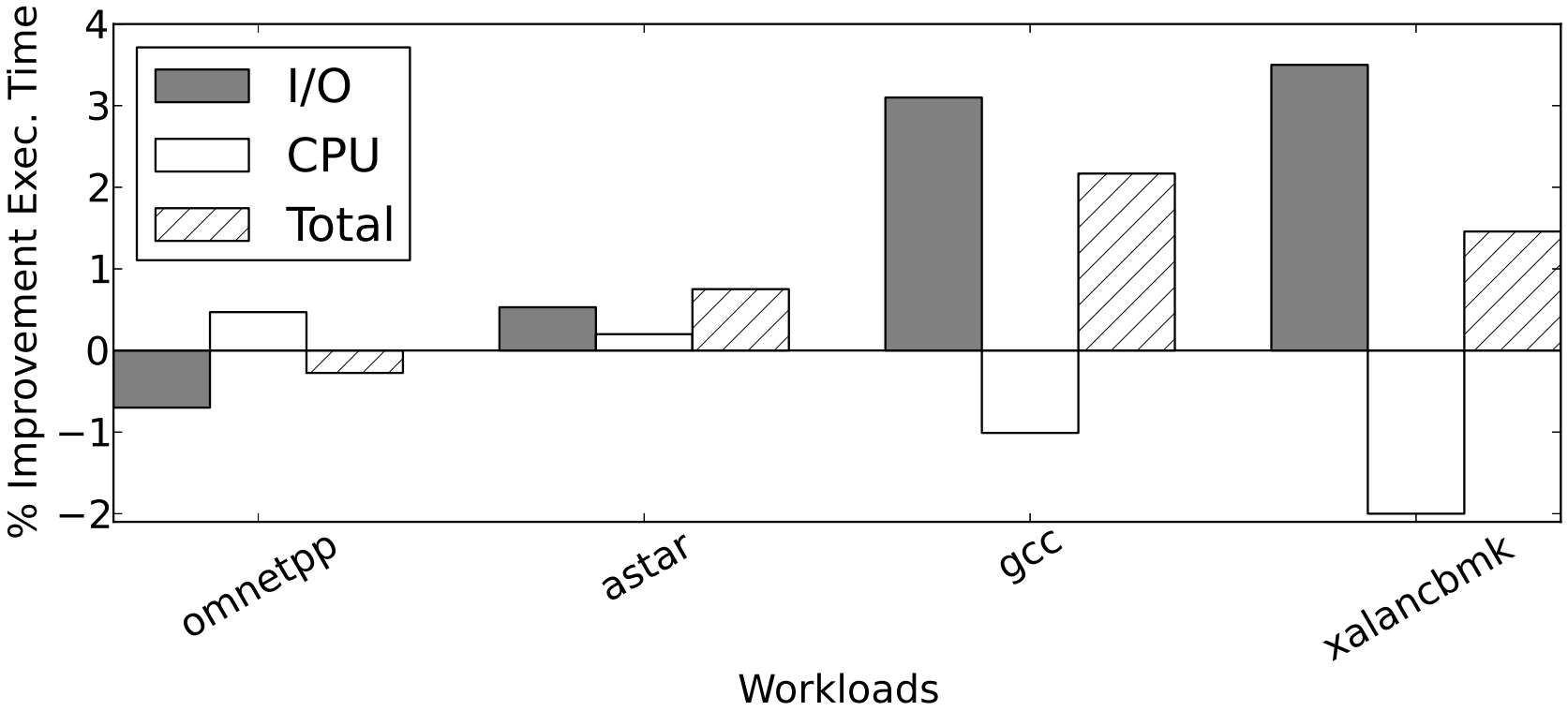

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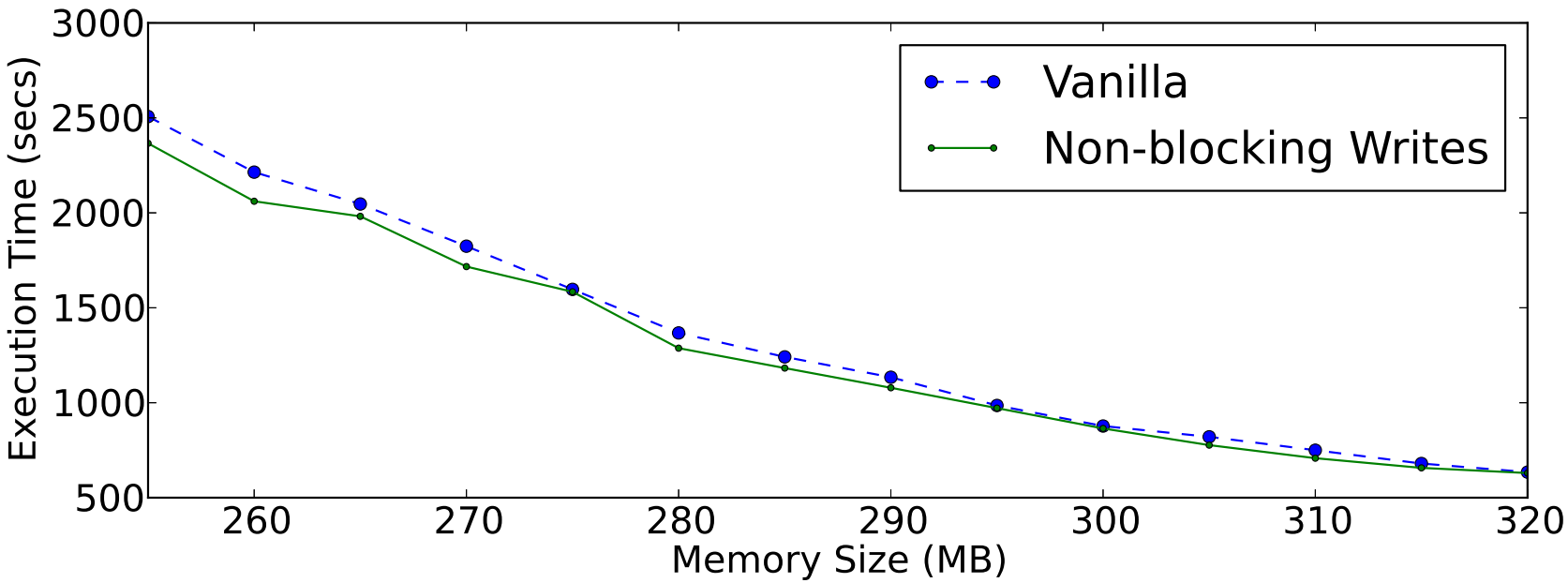
NBW Evaluation: Constrained Memory



- 5 runs per point (<9.5% COV)
- Improvement increase with lower memory
- Up to 7% improvement (260MB)

NBW Scheduling Problem

Up to 8% degradation with multi-threaded apps

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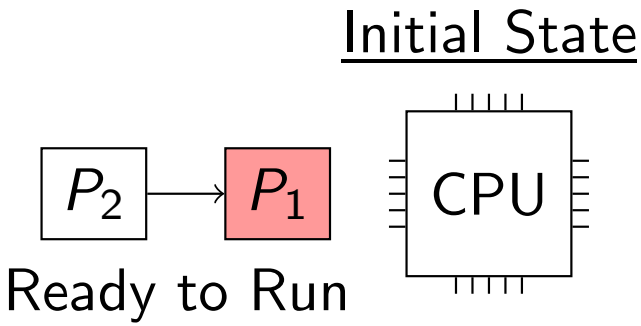

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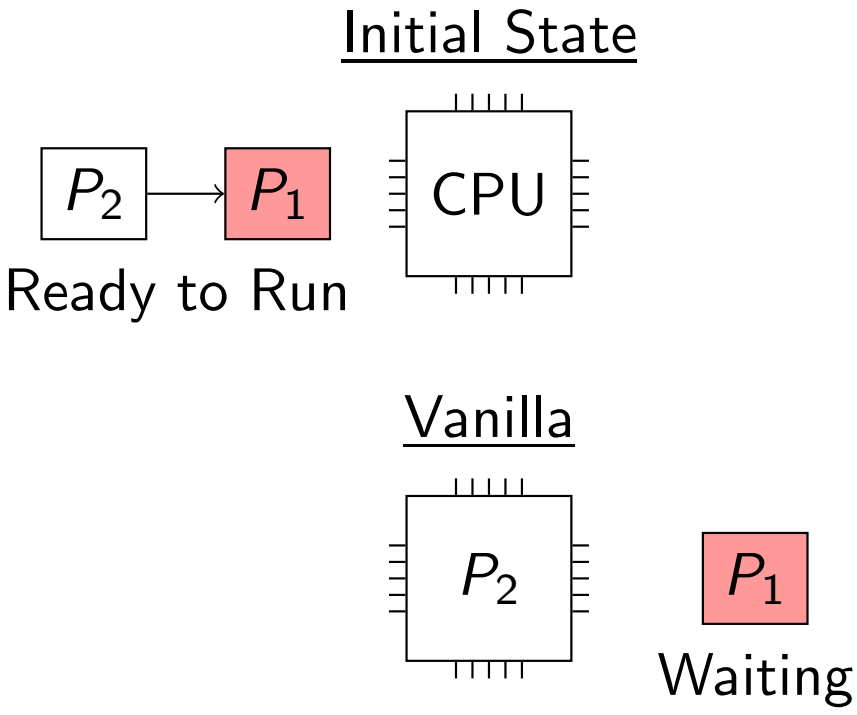

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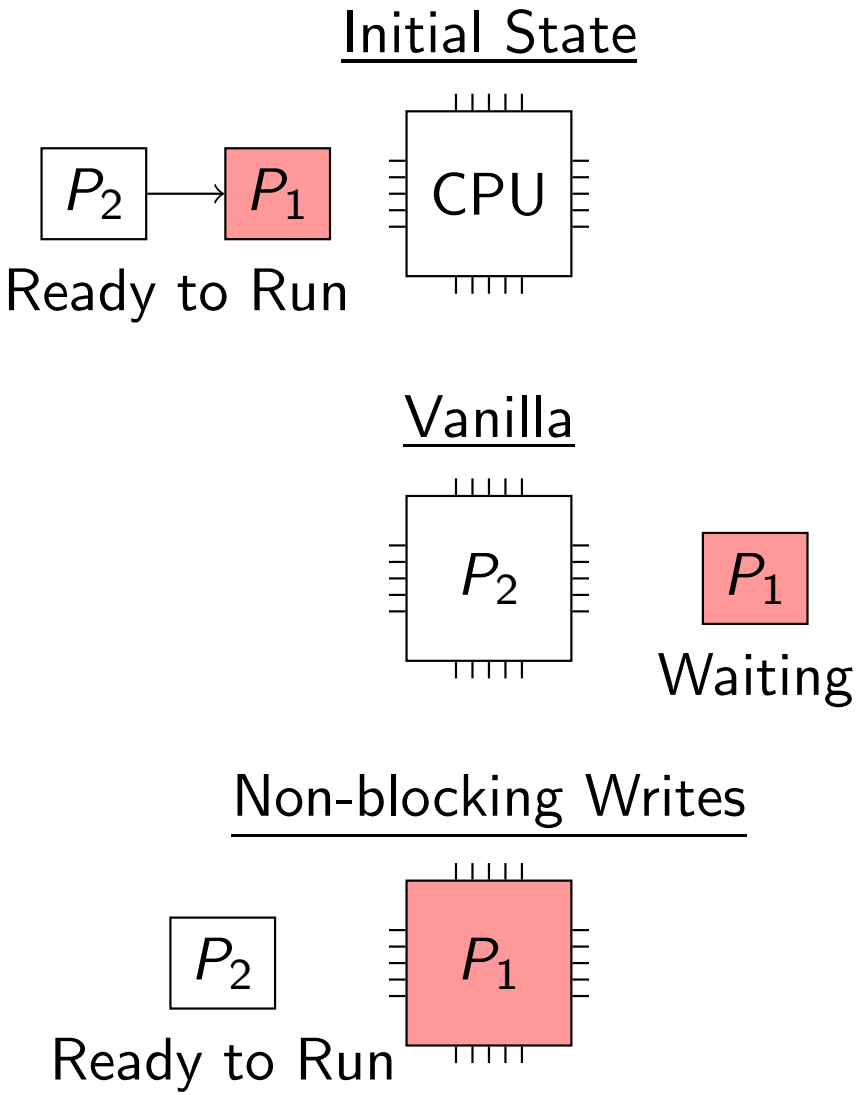

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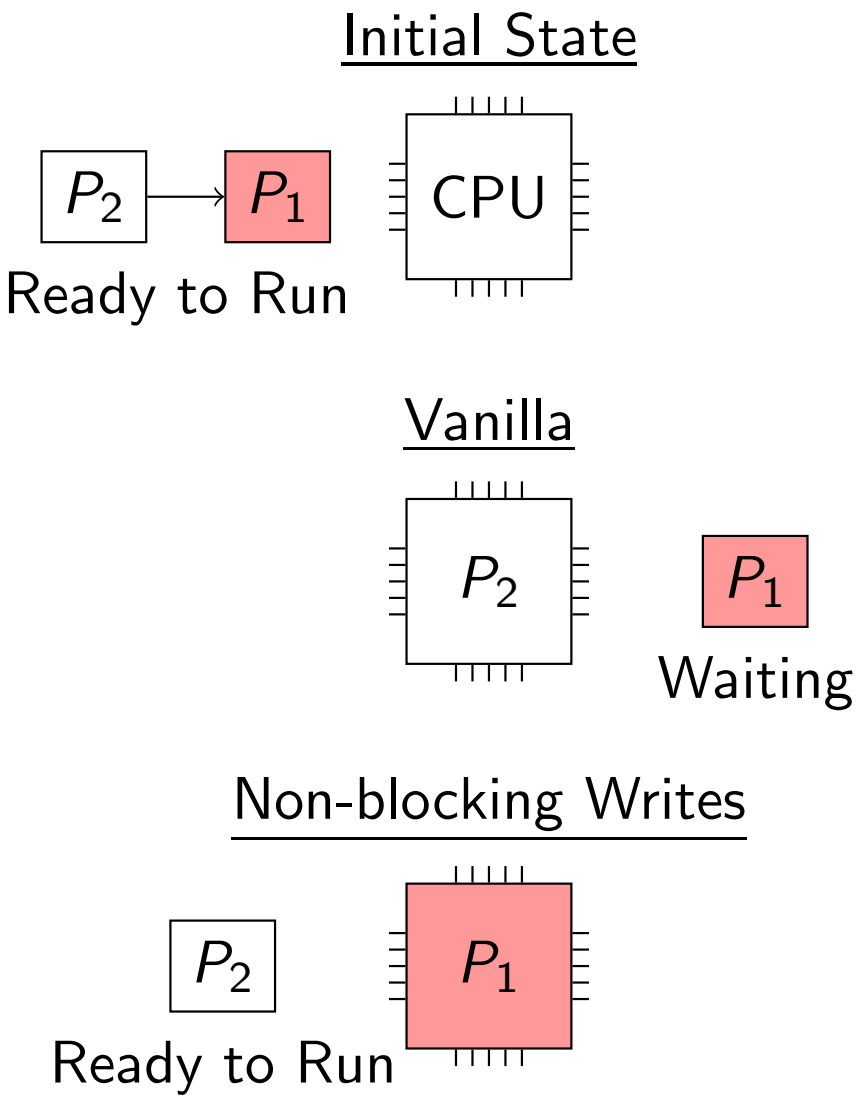
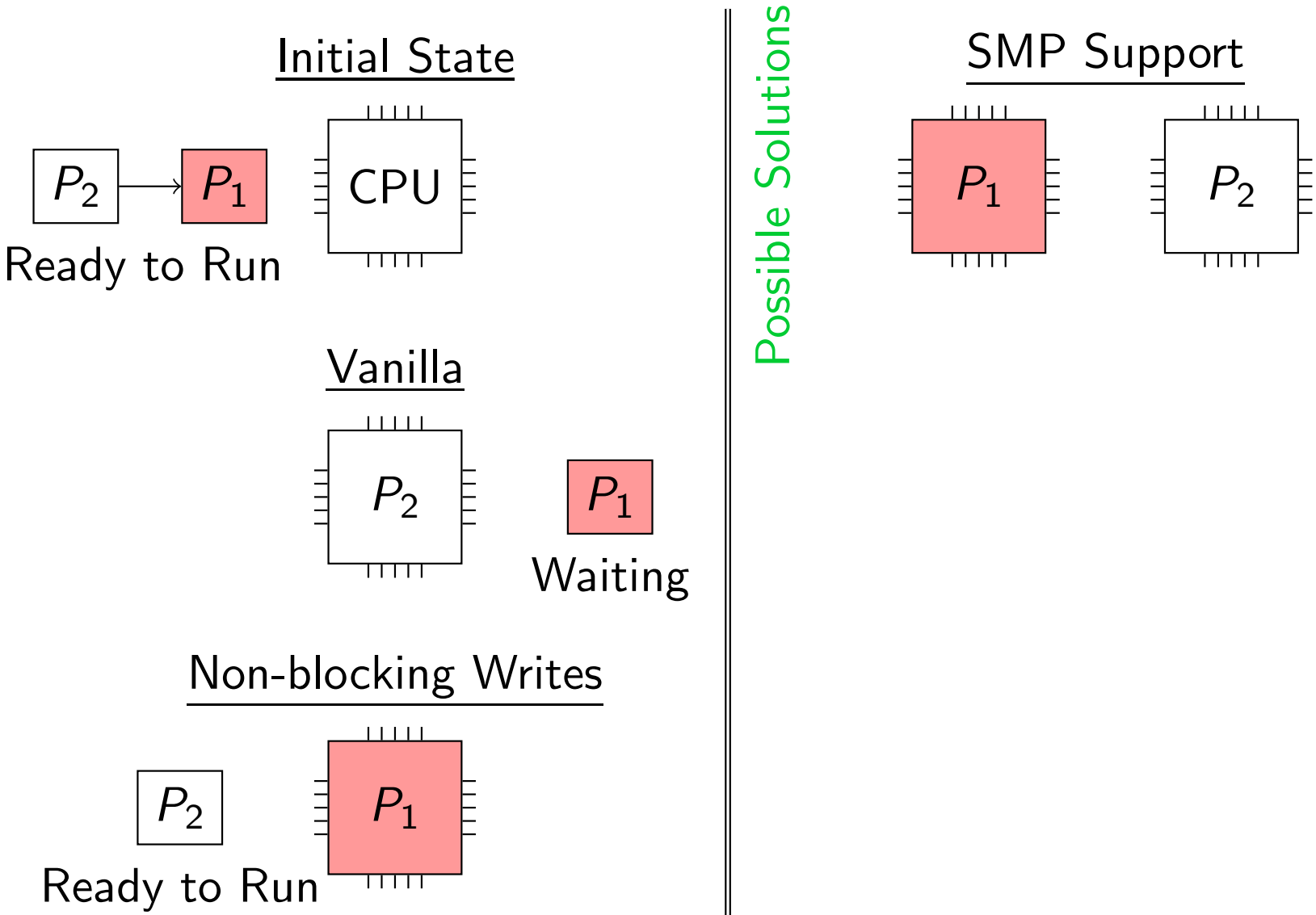


Possible Solutions

NBW Scheduling Problem

Up to 8% degradation with multi-threaded apps



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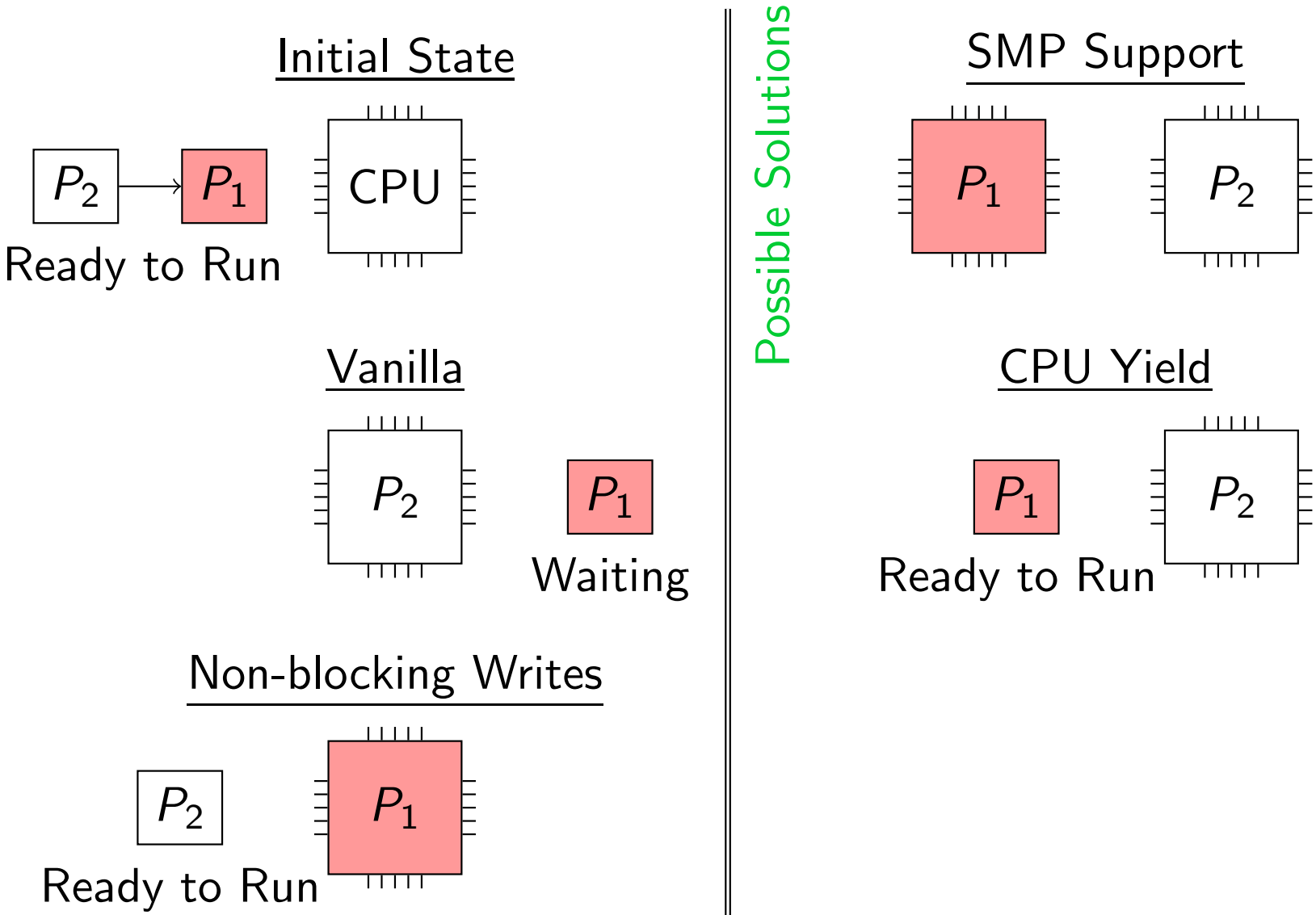
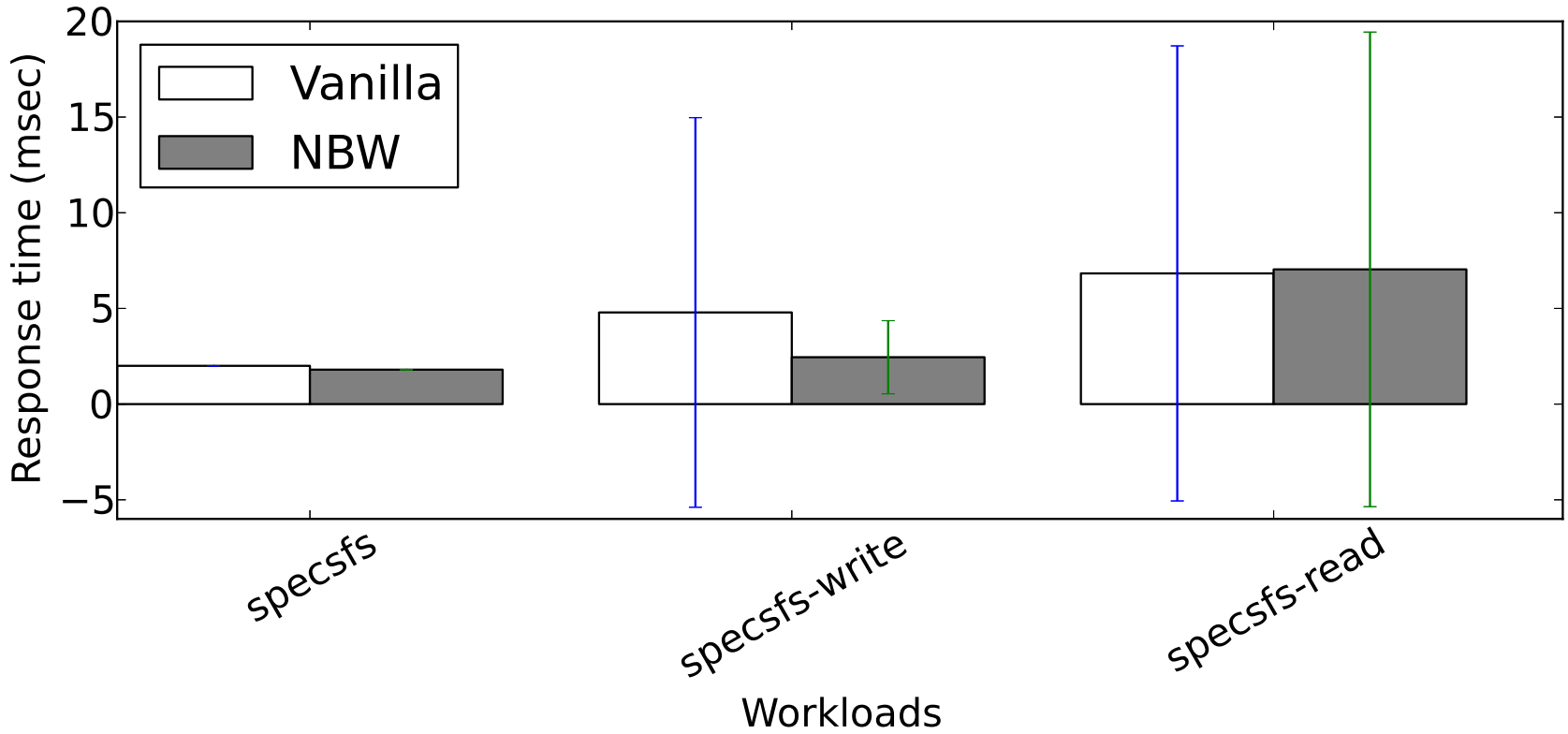


NBW Evaluation: File System Response Time



- 50% write response time reduction in SPEC SFS
- Much lower variance ($10 \rightarrow 2$)
- Read latency remain unchanged

Non-blocking Writes: Summary

- Non-blocking writes allows asynchronous writes to pages not in memory
- Evaluation with server and developer workloads showed:
  - ✓ Up to 7% reduction in execution time for single-threaded applications
  - ✓ 50% reduction in writes response time for file system workloads
  - ✗ Degradation in performance of multi-threaded workloads

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Impact

- Potential to increase idleness of disks in caching systems (SRCMap and EXCES)
- Decouples write response time from backing store performance
- Could improve viability of reduced-memory energy-efficient systems

Conclusions

- It is important to solve the energy problem in disks and memory
- Caching techniques can be used to save energy in disks:
  - ✓ 36%-59% energy savings in multi-disk systems
  - ✓ 2%–14% energy savings in single-disk systems
- We eliminate the page fetch-before-update with NBW:
  - ✓ Improves execution time in single-threaded applications
  - ✓ Write latency in file server workloads
  - ✓ Solutions proposed to sub-optimal scheduling problem in multi-threaded apps
  - ✓ Potential to improve power in EXCES and SRCMap
  - ✓ Potential to improve performance in resource constrained systems

Future Work

The Memory Challenge

- SSDs are becoming more popular $\Rightarrow$ Storage energy share will be smaller
- DRAM size continues to increase

Direction 1

Explore the effectiveness of reducing memory with NBW help

Direction 2

Use NBW to artificially reduce the page size

Publications (Presented Here)

Publication	Refs.
Design and Implementation of Non-blocking Writes Luis Useche, Ricardo Koller, Jesus Ramos, Raju Rangaswami, *Under Review*	–
Truly Non-blocking Writes Luis Useche, Ricardo Koller, Raju Rangaswami, Akshat Verma, *HotStorage 2011*	–
SRCMap: Energy Proportional Storage Using Dynamic Consolidation Akshat Verma, Ricardo Koller, Luis Useche, Raju Rangaswami, *FAST 2010*	23
EXCES: EXternal Caching in Energy Saving Storage Systems Luis Useche, Jorge Guerra, Medha Bhadkamkar, Mauricio Alarcon, and Raju Rangaswami *HPCA 2008*	22

Additional Publications

Publication	Refs.
BORG: Block-reORGanization for Self-optimizing Storage Systems Medha Bhadkamkar, Jorge Guerra, Luis Useche, Sam Burnett, Jason Liptak, Raju Rangaswami and, Vagelis Hristidis *FAST 2009*	53
The Case for Active Block Layer Extensions Jorge Guerra, Luis Useche, Medha Bhadkamkar, Ricardo Koller, and Raju Rangaswami *SPEED 2008*	3

Aknowledgement

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