CS 471 Operating Systems

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Announcement

- Deadline of OS/161 Project 2 is extended by one week to May 3rd

Disk vs. Flash

Disk Overview

- I/O requires: seek, rotate, transfer
- Inherently:
  - Not parallel (only one head)
  - Slow (mechanical)
  - Poor random I/O (locality around disk head)
- Random requests each taking ~10+ ms

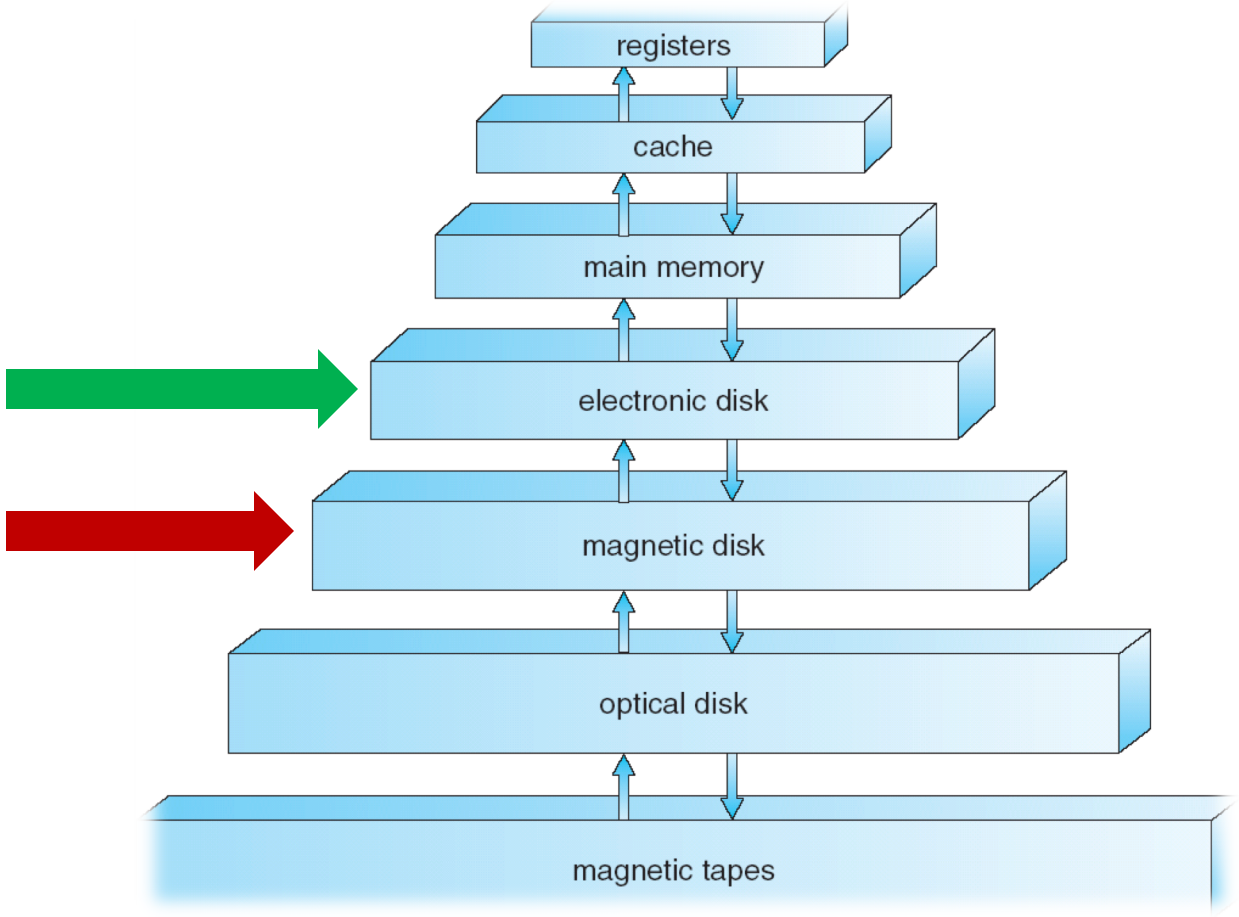
Flash Overview

- Hold charge in cells. No moving (mechanical) parts!
- Inherently parallel!
- No seeks!

Storage Hierarchy Overview

Flash:
Smaller capacity
Faster accesses

HDD:
Larger capacity
Way slower accesses



Disks vs. Flash: Performance

- Throughput
  - Disk: ~130MB/s (sequential)
  - Flash: ~400MB/s

- Latency
  - Disk: ~10ms (one op)
  - Flash:
    - Read: 10-50us
    - Program: 200-500us
    - Erase: 2ms

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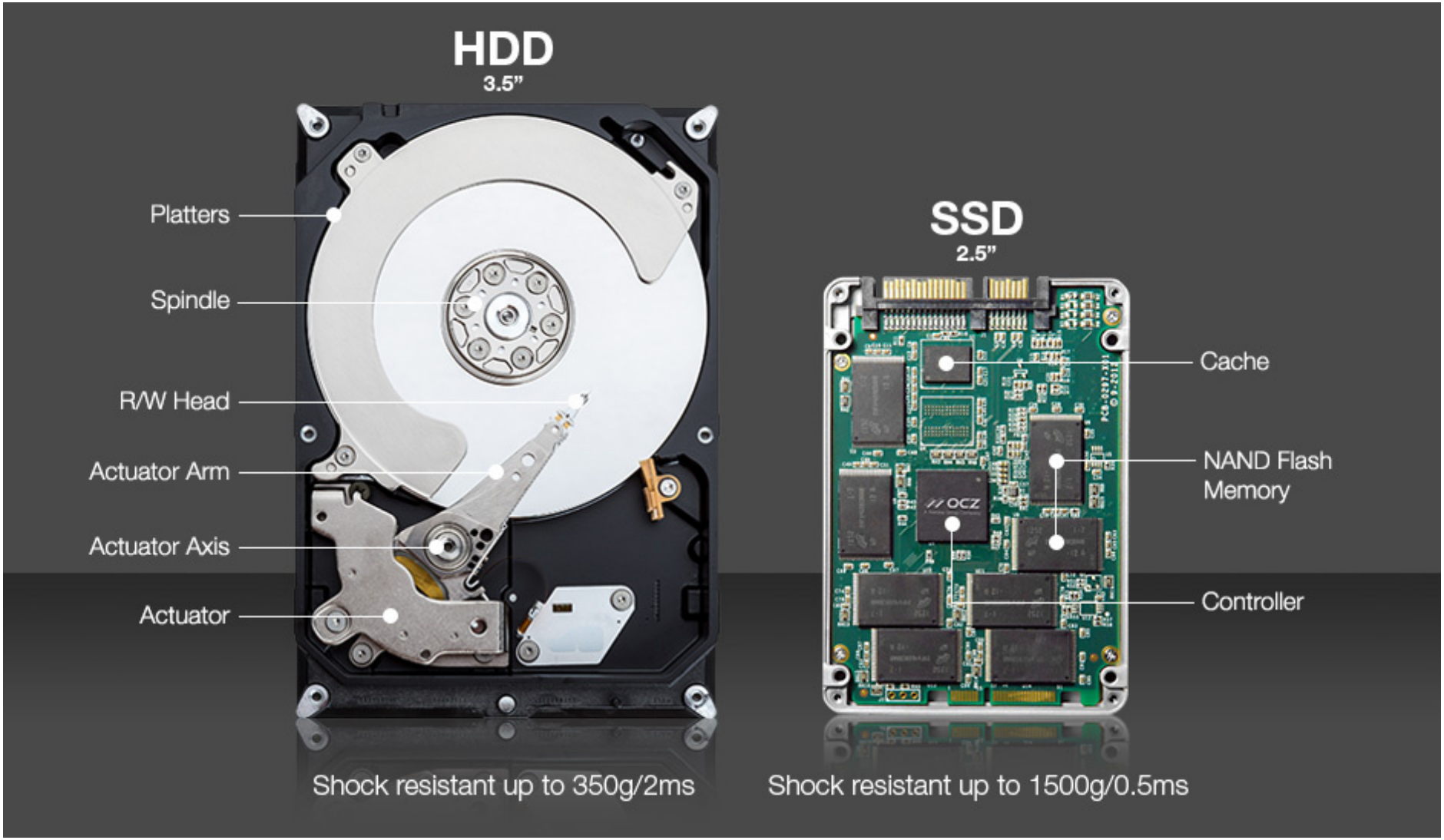
Types of write, more later…

Disks vs. Flash: Internal



* https://www.enterprisestorageforum.com/storage-hardware/ssd-vs-hdd.html

Disks vs. Flash: Capacity

An obvious question is why are we talking about spinning disks at all, rather than SSDs, which have higher IOPS and are the "future" of storage. The root reason is that the cost per GB remains too high, and more importantly that **the growth rates in capacity/$ between disks and SSDs are relatively close** (at least for SSDs that have sufficient numbers of program-erase cycles to use in data centers), so that cost will not change enough in the coming decade. We do make extensive use of SSDs, but primarily for high performance workloads and caching, and this helps disks by shifting seeks to SSDs.

~ Eric Brewer et al. Google

Source: http://static.googleusercontent.com/media/research.google.com/en//pubs/archive/44830.pdf

	SSD	HDD
Price	$0.25-$0.27 per GB average	$0.2-$0.03 per GB average

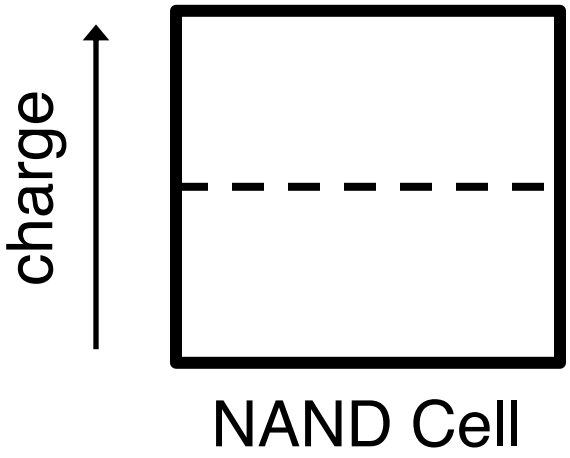
Disks vs. Flash: Summary

	SSD	HDD
Price	$0.25-$0.27 per GB average	$0.2-$0.03 per GB average
Lifespan	30-80% test developed bad block in their lifetime	3.5% developed bad sectors comparatively
Ideal for	High performance processing Residing in APA or Tier 0/1 media in hybrid arrays	High capacity nearline tiers Long-term retained data
Read/write speeds	200 MB/s to 2500 MB/s	up to 200 MB/s
Benefits	Higher performance for faster read/write operations and fast load times	Less expensive Mature technology and massive installed user base
Drawbacks	May not be as durable/reliable as HDDs Not good for long-term archival data	Mechanical components take longer to read-write than SSDs

* https://www.enterprisestorageforum.com/storage-hardware/ssd-vs-hdd.html

Flash Architecture

SLC: Single-Level Cell



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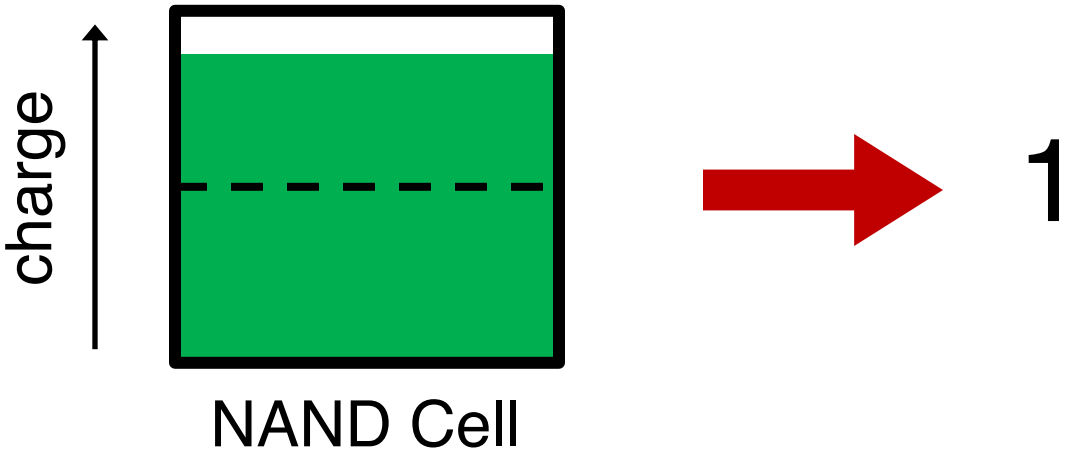

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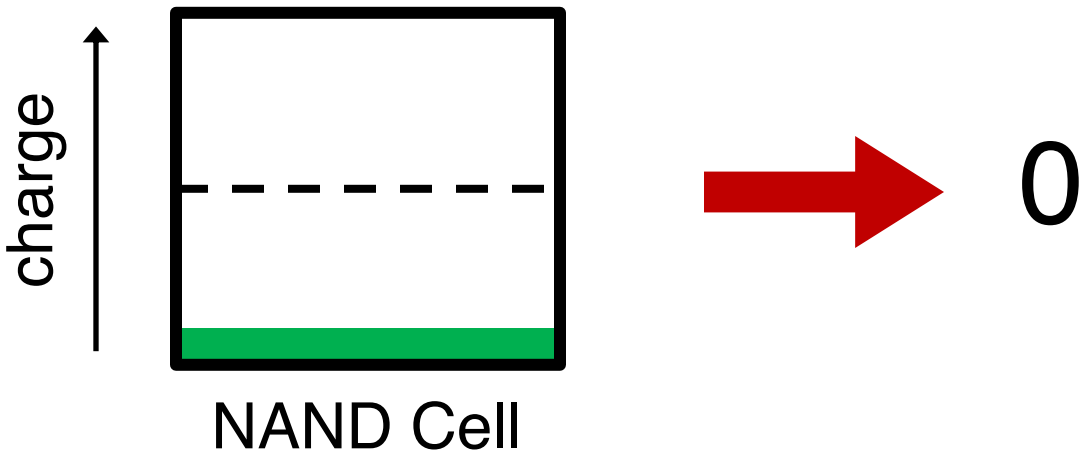
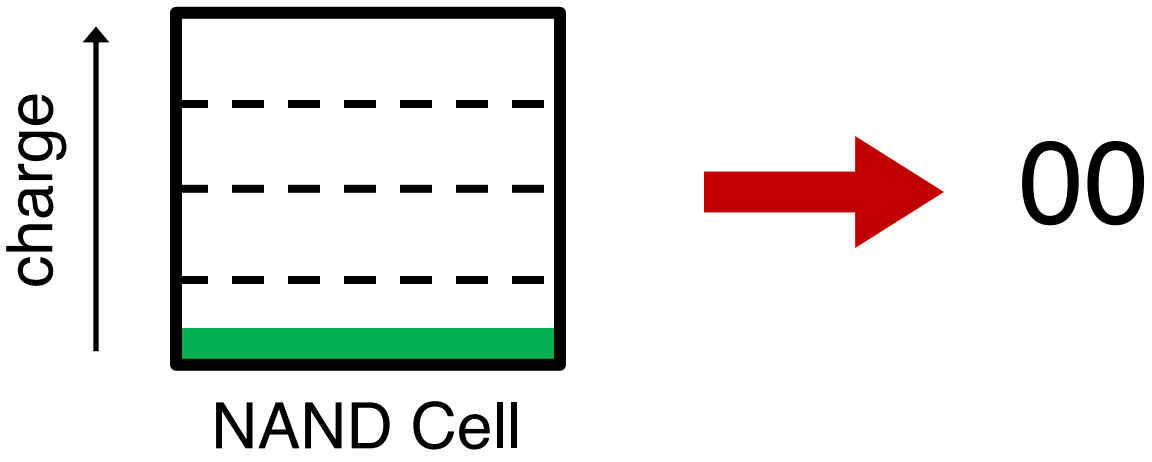


MLC: Multi-Level Cell



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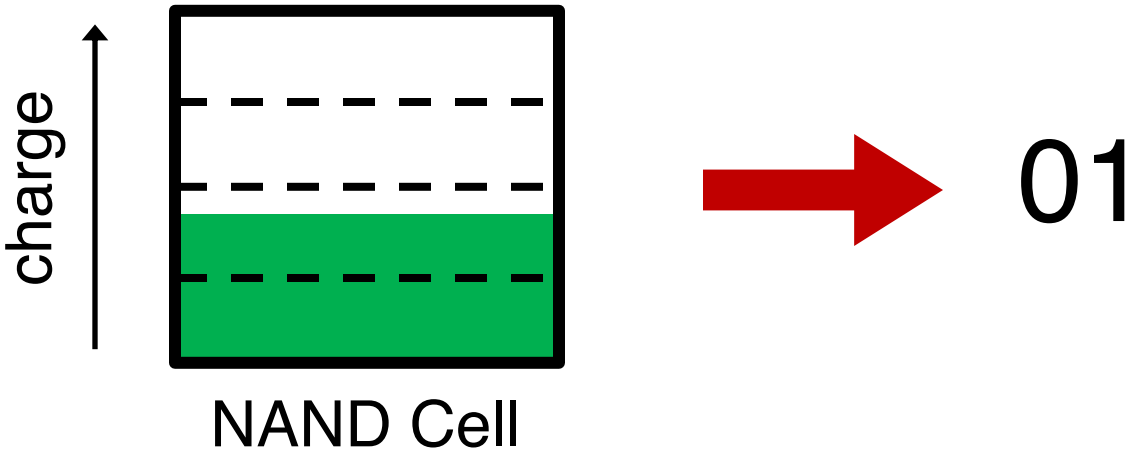

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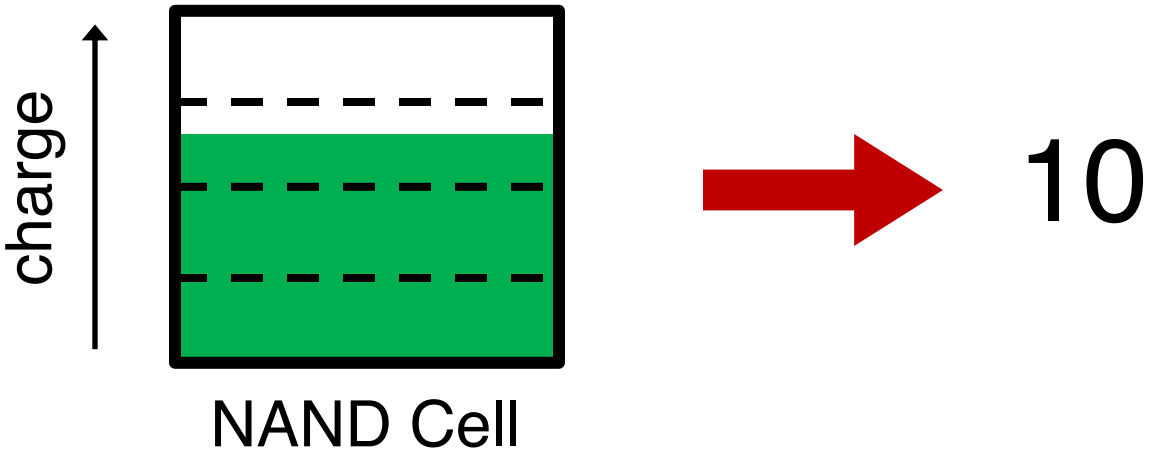

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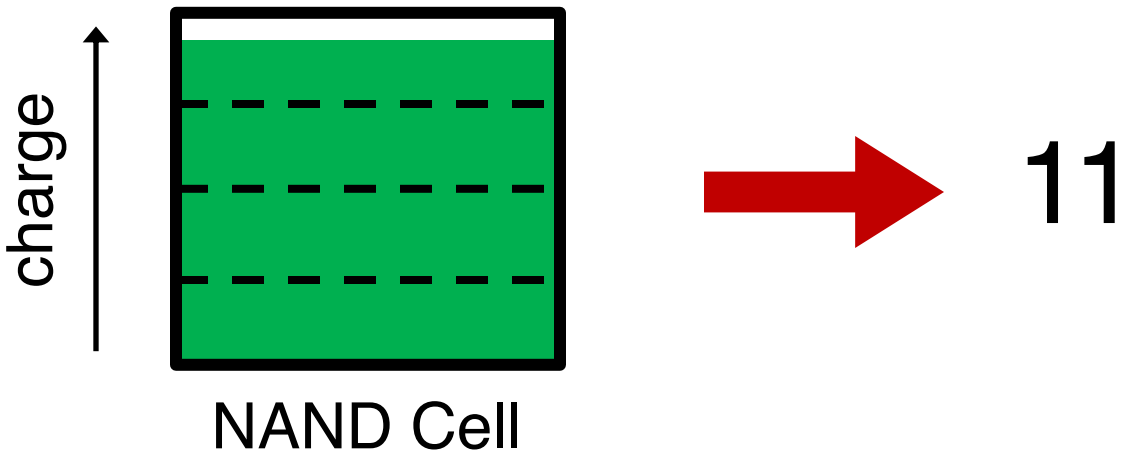
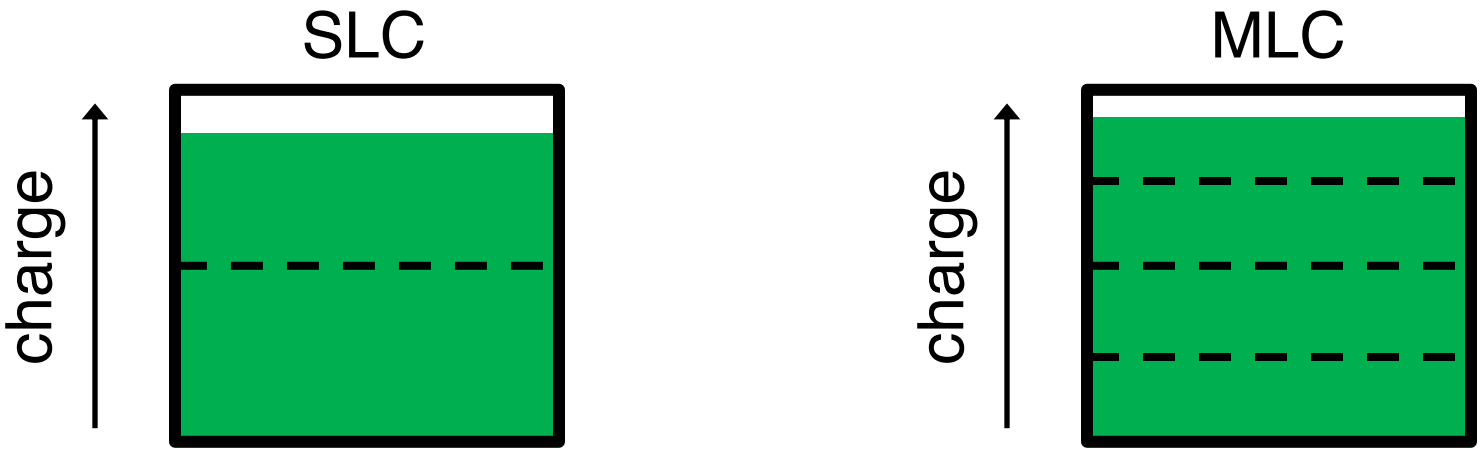


Single- vs. **M**ulti-**L**evel **C**ell



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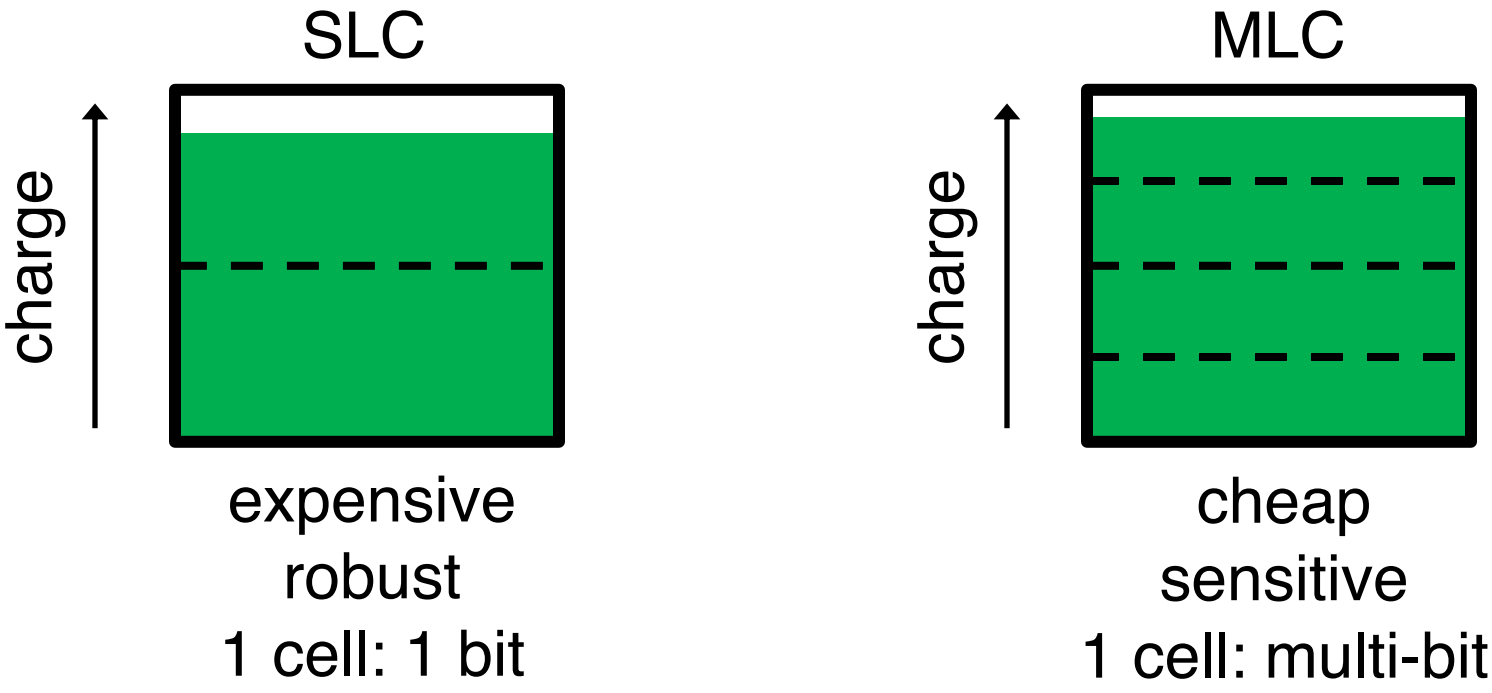


Wearout

- Problem: flash cells wear out after being erased too many times

- MLC: ~10K times
- SLC: ~100K times

- Usage strategy: **???**

Wearout

- Problem: flash cells wear out after being erased too many times

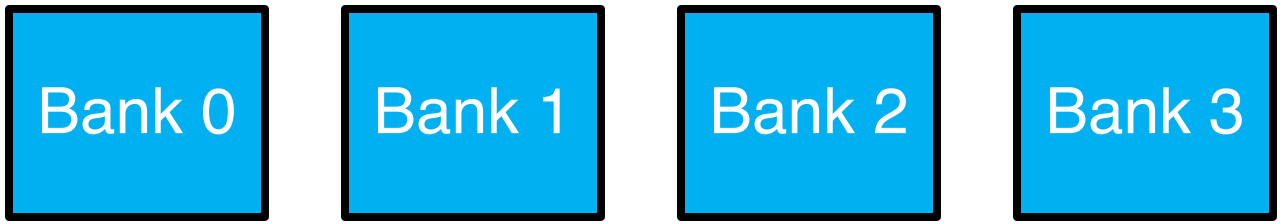
- MLC: ~10K times
- SLC: ~100K times

- Usage strategy: wear leveling
  - Prevents some cells from being wornout while others still fresh

Banks

- Flash devices are divided into banks (aka. planes)

- Banks can be accessed in parallel



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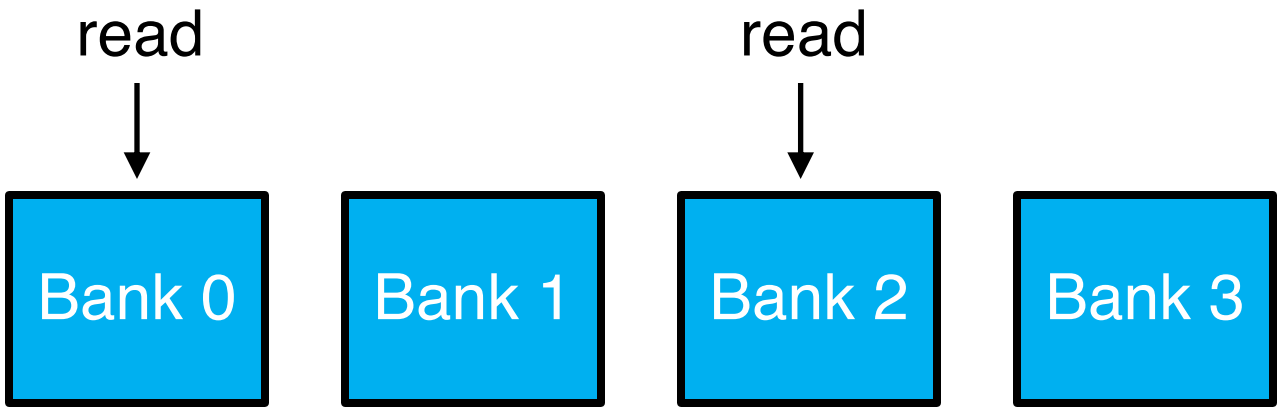

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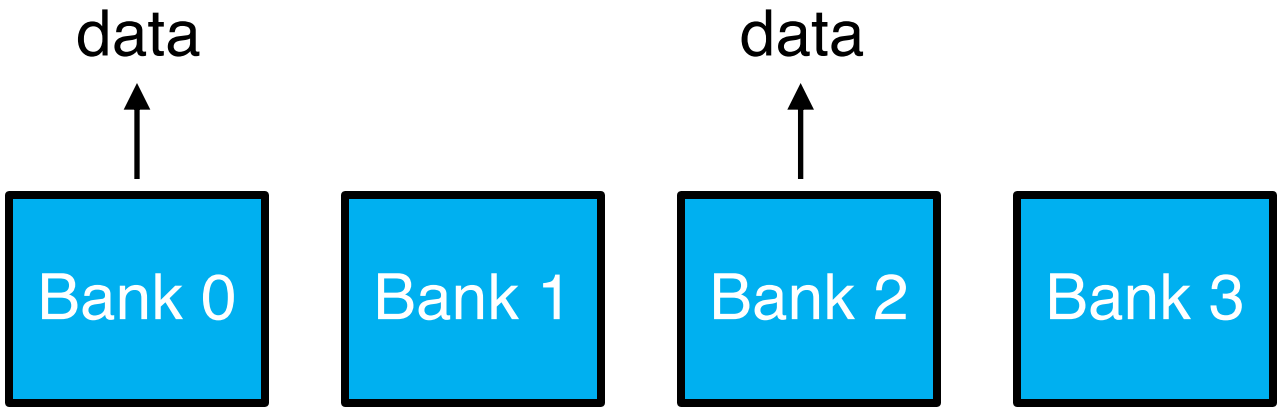


Flash Writes

- Writing 0's
  - Fast, fine-grained
- Writing 1's
  - Slow, coarse-grained

Flash Writes

- Writing 0's
  - Fast, fine-grained
  - called "**program**"
- Writing 1's
  - Slow, coarse-grained
  - called "**erase**"

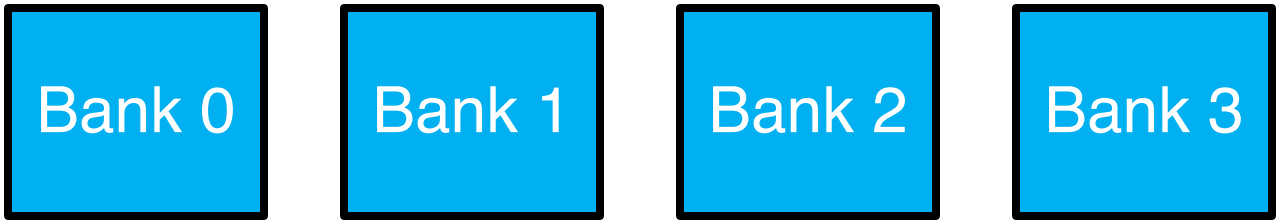
Flash Writes

- Writing 0's
  - Fast, fine-grained [page-level]
  - called "**program**"
- Writing 1's
  - Slow, coarse-grained [block-level]
  - called "**erase**"

Flash Writes

- Writing 0's
  - Fast, fine-grained [page-level]
  - called "**program**"
- Writing 1's
  - Slow, coarse-grained [block-level]
  - called "**erase**"
- Flash can only "write" (program) into **clean** pages
  - "**clean**": pages containing all 1's (pages that have been erased)
  - Flash does not support in-place overwrite!

Banks and Blocks



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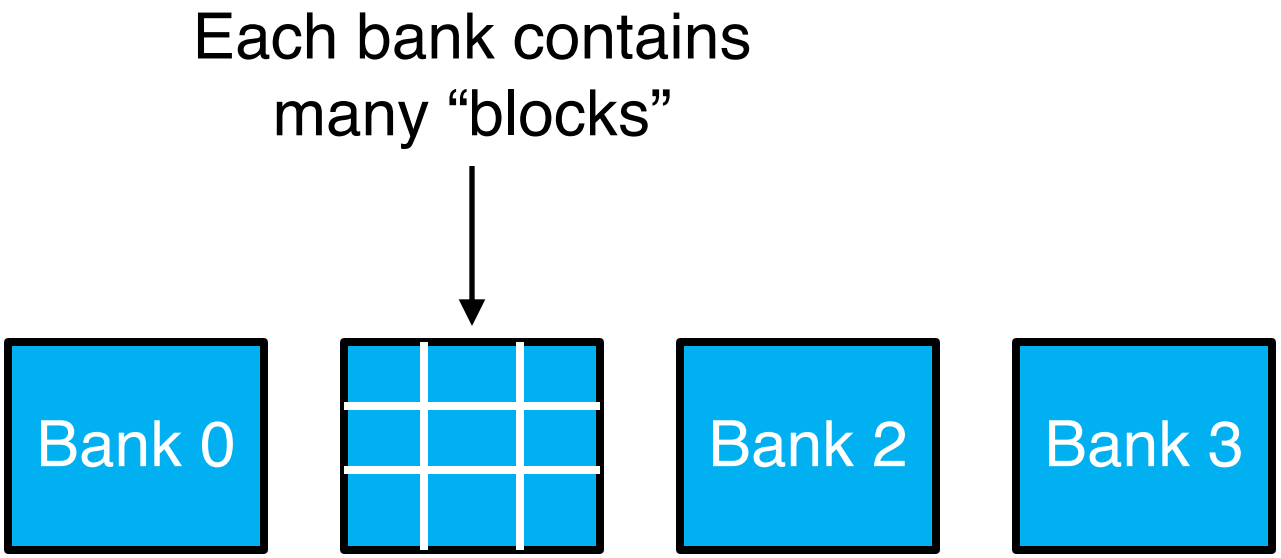
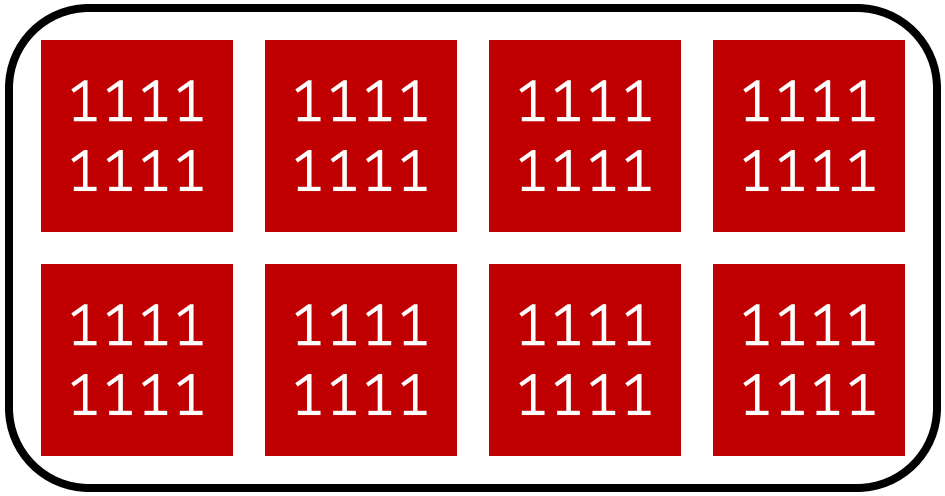
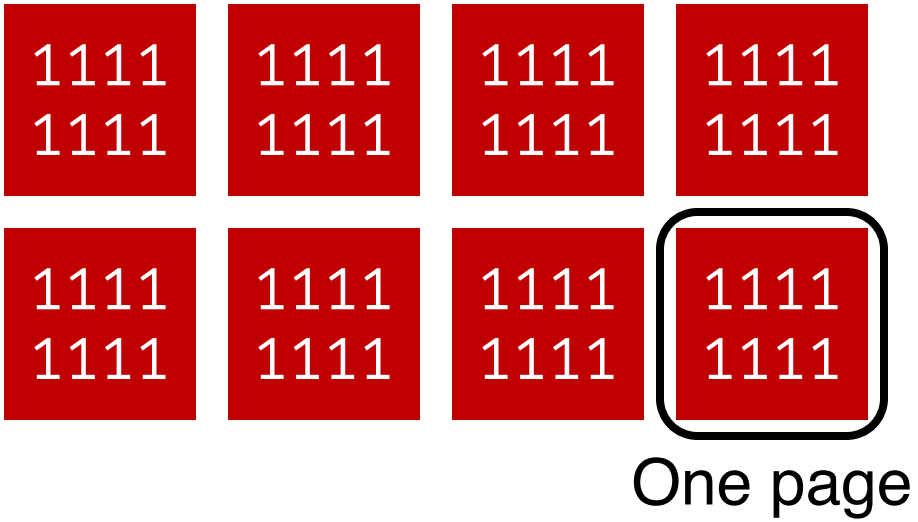


Block and Pages

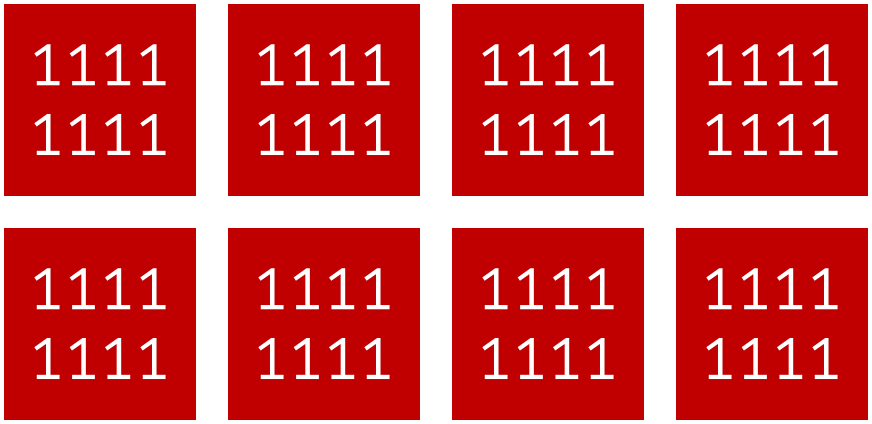


One block

Block and Pages

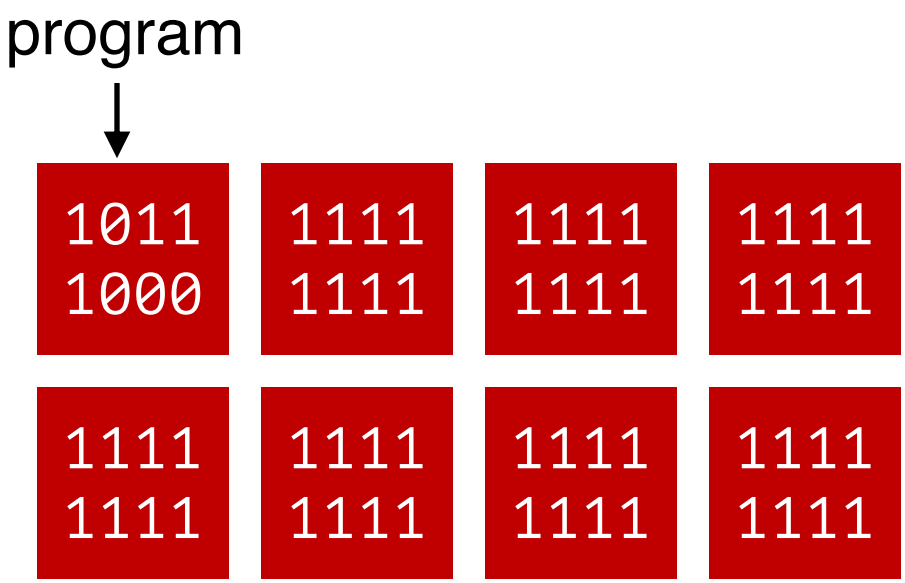


Block and Pages



All pages are clean
(“programmable”)

Block


program
1011
1000
1111
1111
1111
1111
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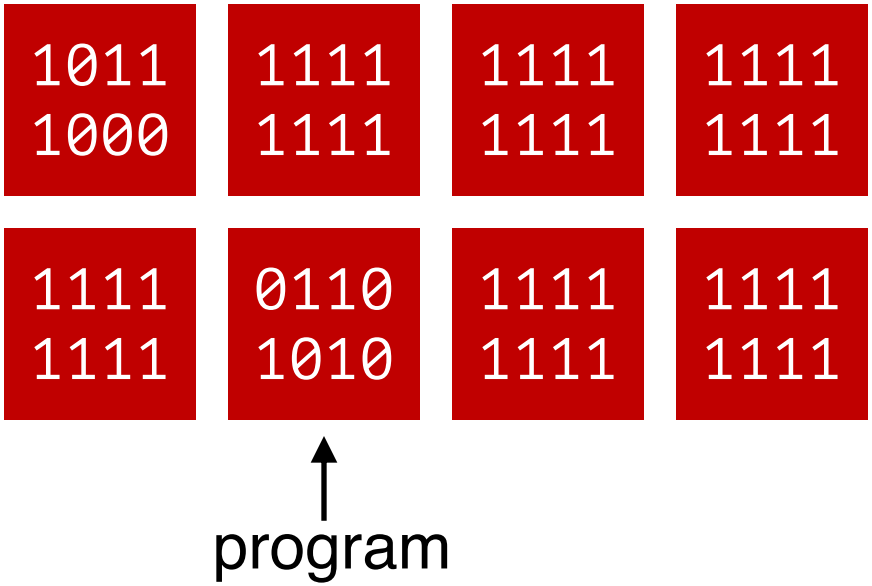
1111
1111
1111
1111

Block


1011
1000
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0110
1010
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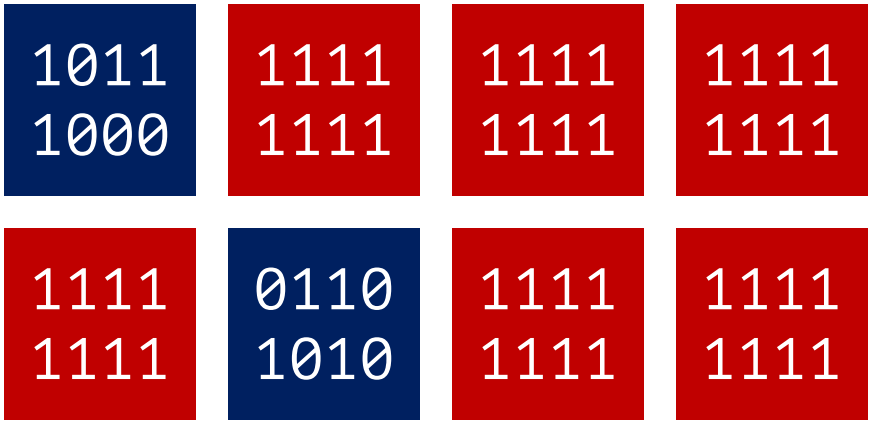
1111
1111
program

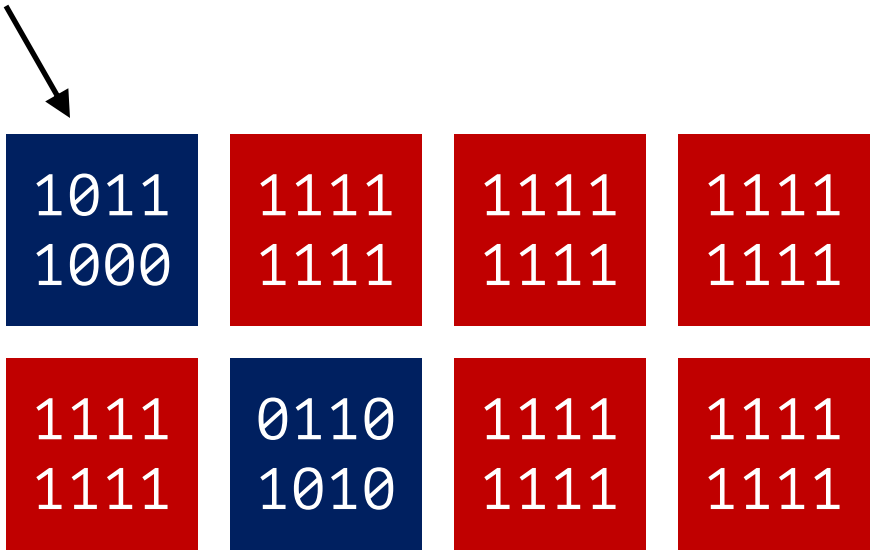
Block



Two pages hold data
(**cannot be overwritten**)

Block

still want to write data into this page???



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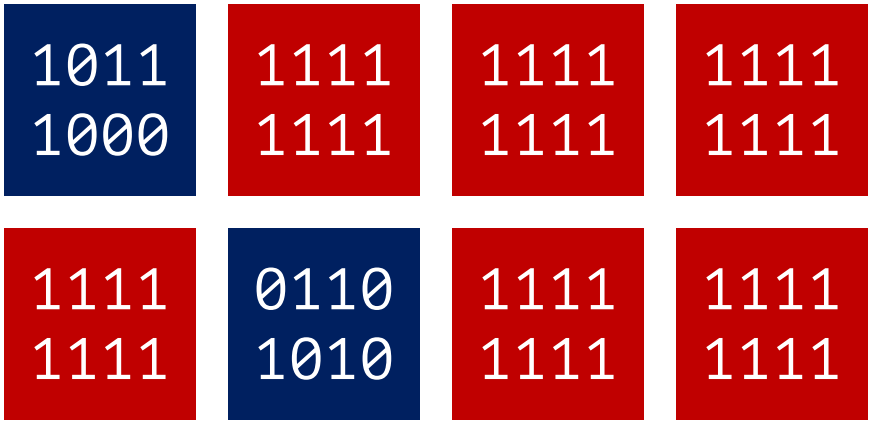
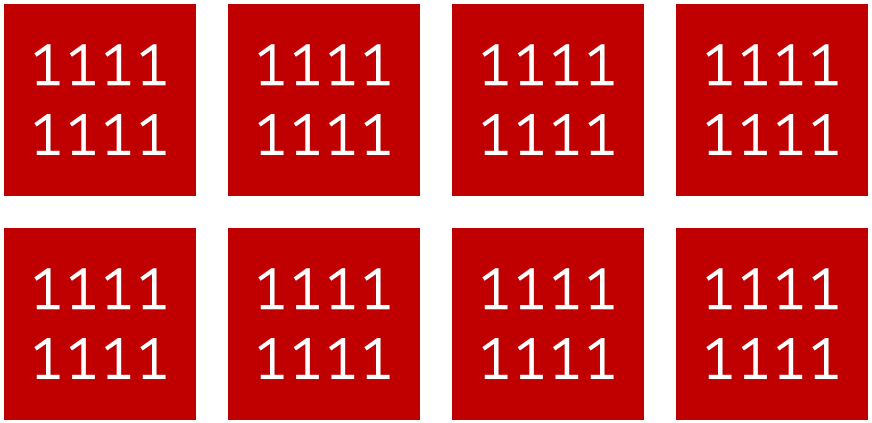

1011
1000
1111
1111
1111
1111
1111
1111
1111
1111
0110
1010
1111
1111
1111
1111

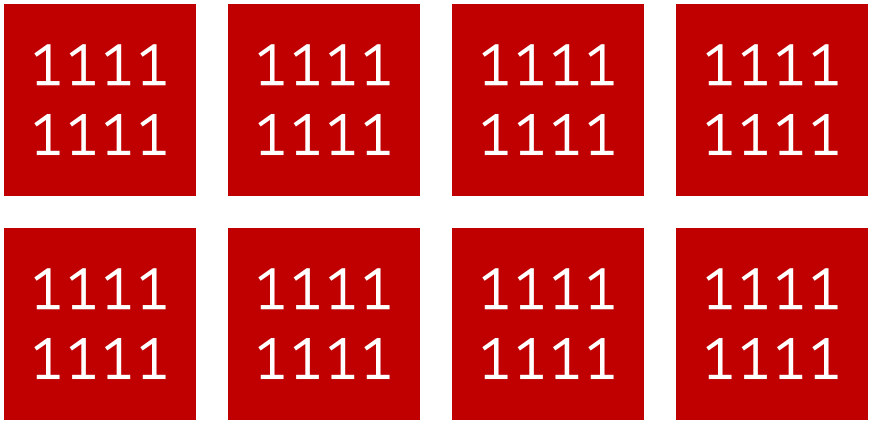
erase

Block



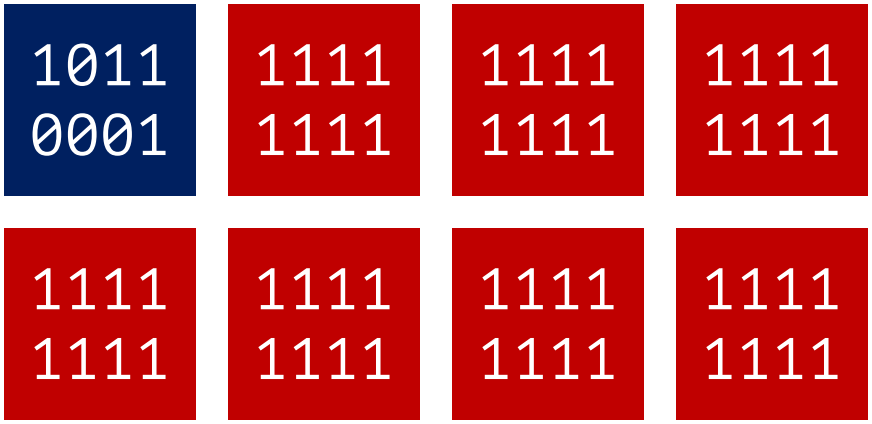
erase
(the whole block)

Block



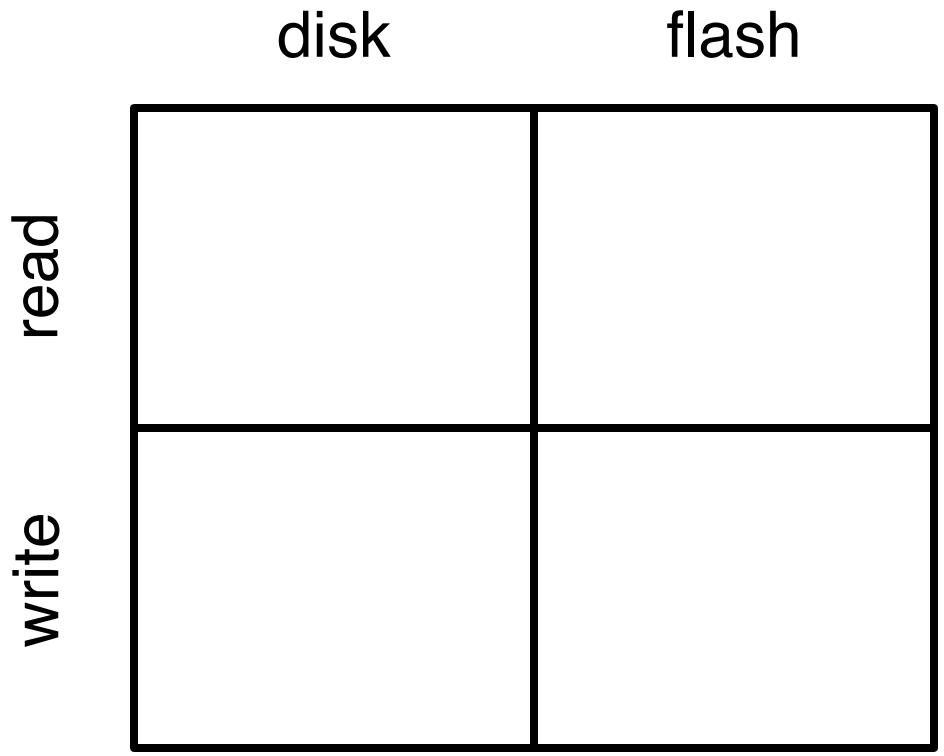
After erase, again, **free state**
(can write new data in any page)

Block



This blue page holds data

Flash vs. Disks: APIs



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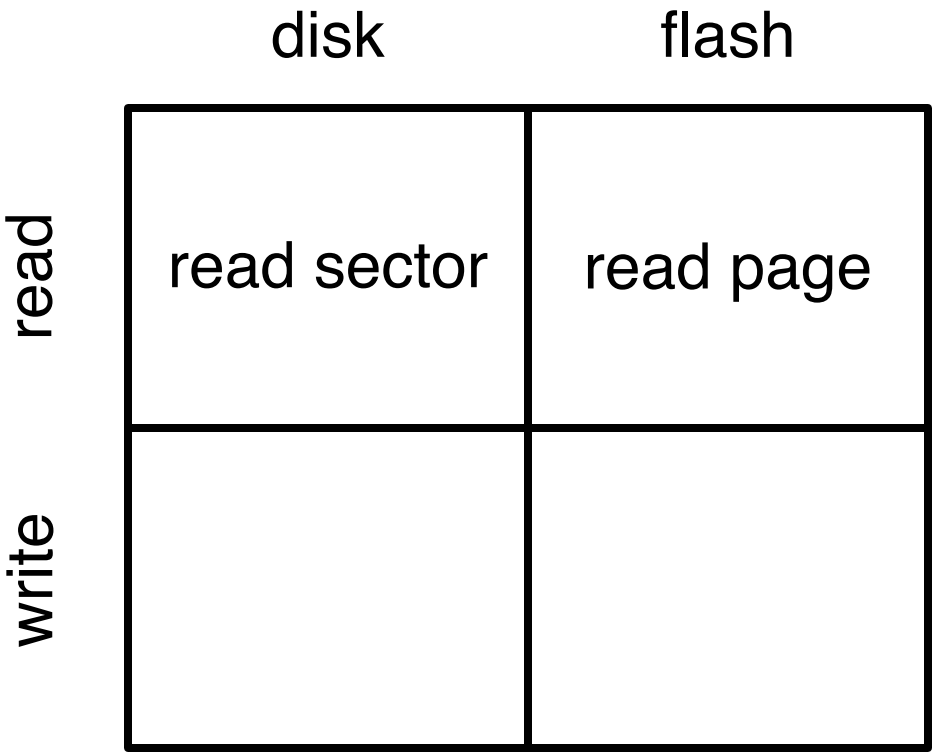

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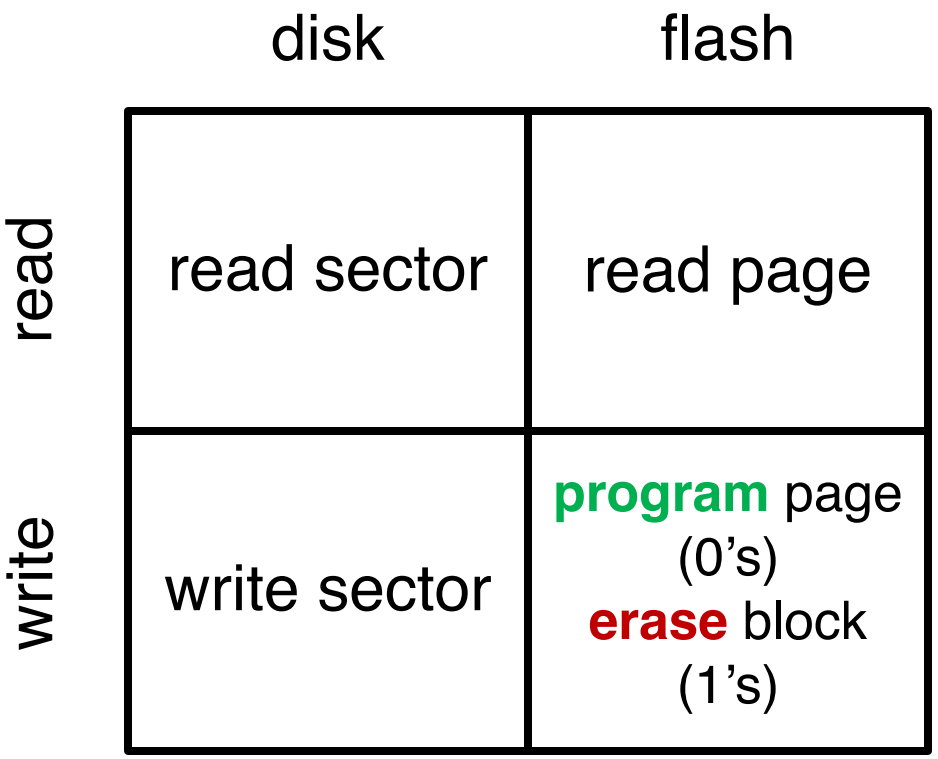

Flash Architecture

- **Bank/plane**: 1024 to 4096 blocks
  - Banks accessed in parallel
- **Block**: 64 to 256 pages
  - Unit of erase
- **Page**: 2 to 8 KB
  - Unit of read and program

Disks vs. Flash: Performance

- Throughput
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- Latency
  - Disk: ~10ms (one op)
  - Flash:
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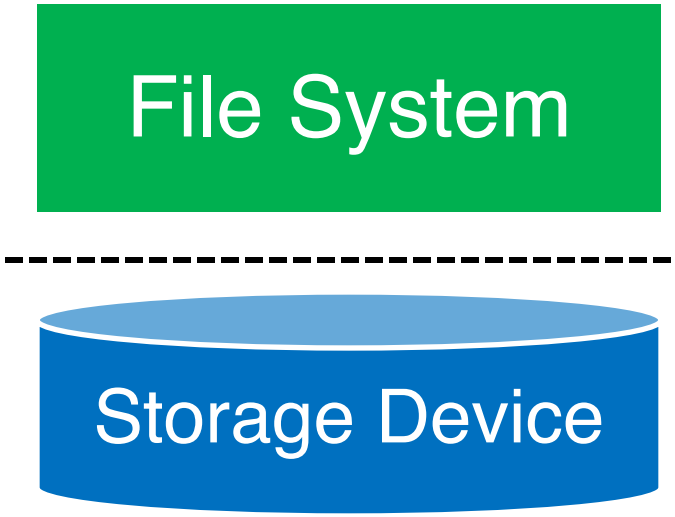
    - **Erase**: 2ms

Working with File System

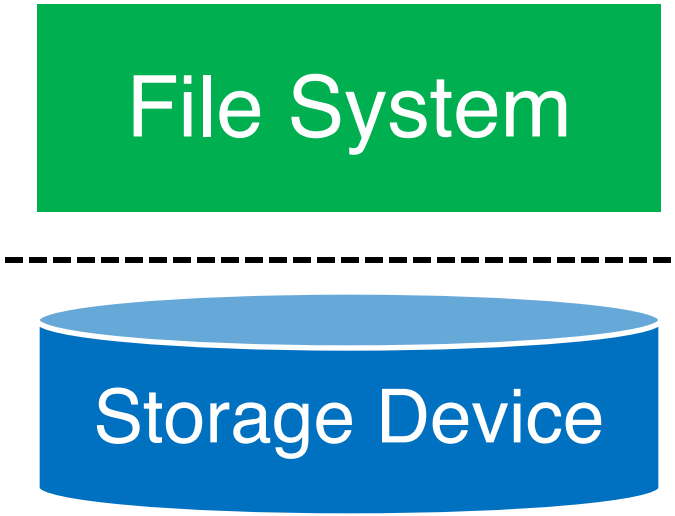
Traditional File Systems



Traditional API:

- read sector
- write sector

Traditional File Systems



Traditional API:

- read sector
- write sector

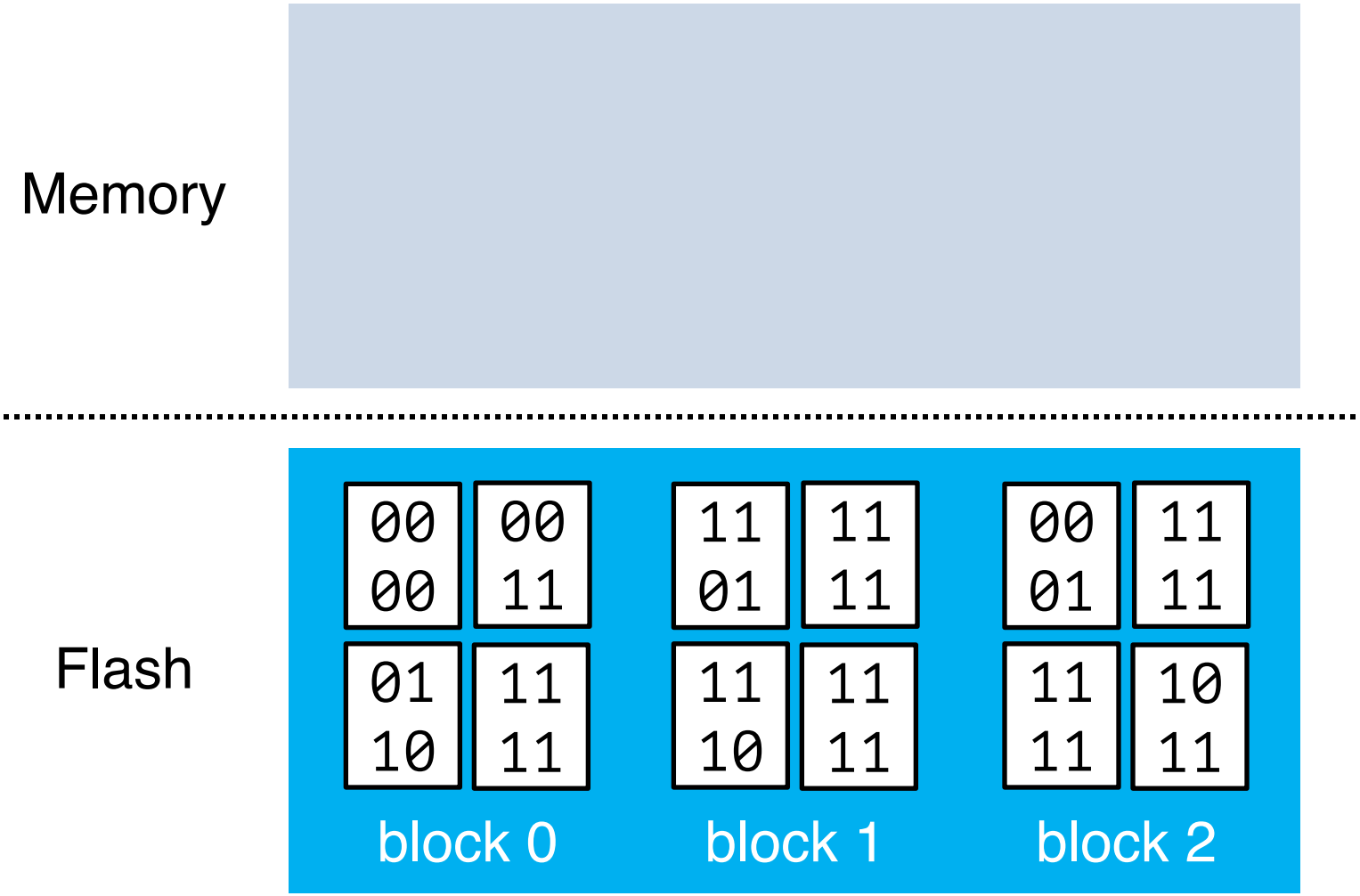
Mismatch with flash!

Traditional APIs wrapping around Flash APIs

```
read(addr):
    return flash_read(addr)

write(addr, data):
    block_copy = flash_read(all pages of block)
    modify block_copy with data
    flash_erase(block of addr)
    flash_program(all pages of block_copy)
```

Awkward Flash Write



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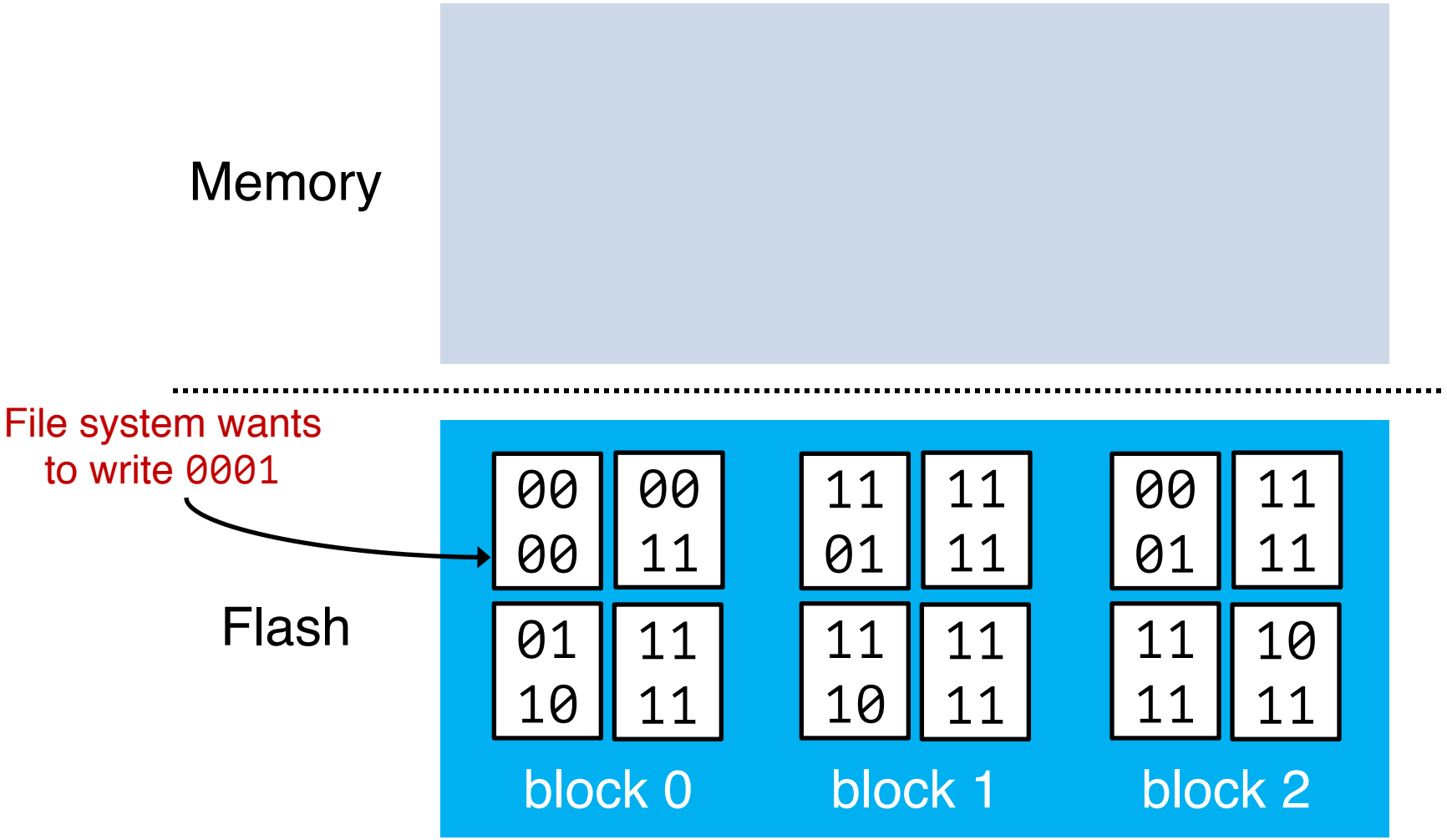

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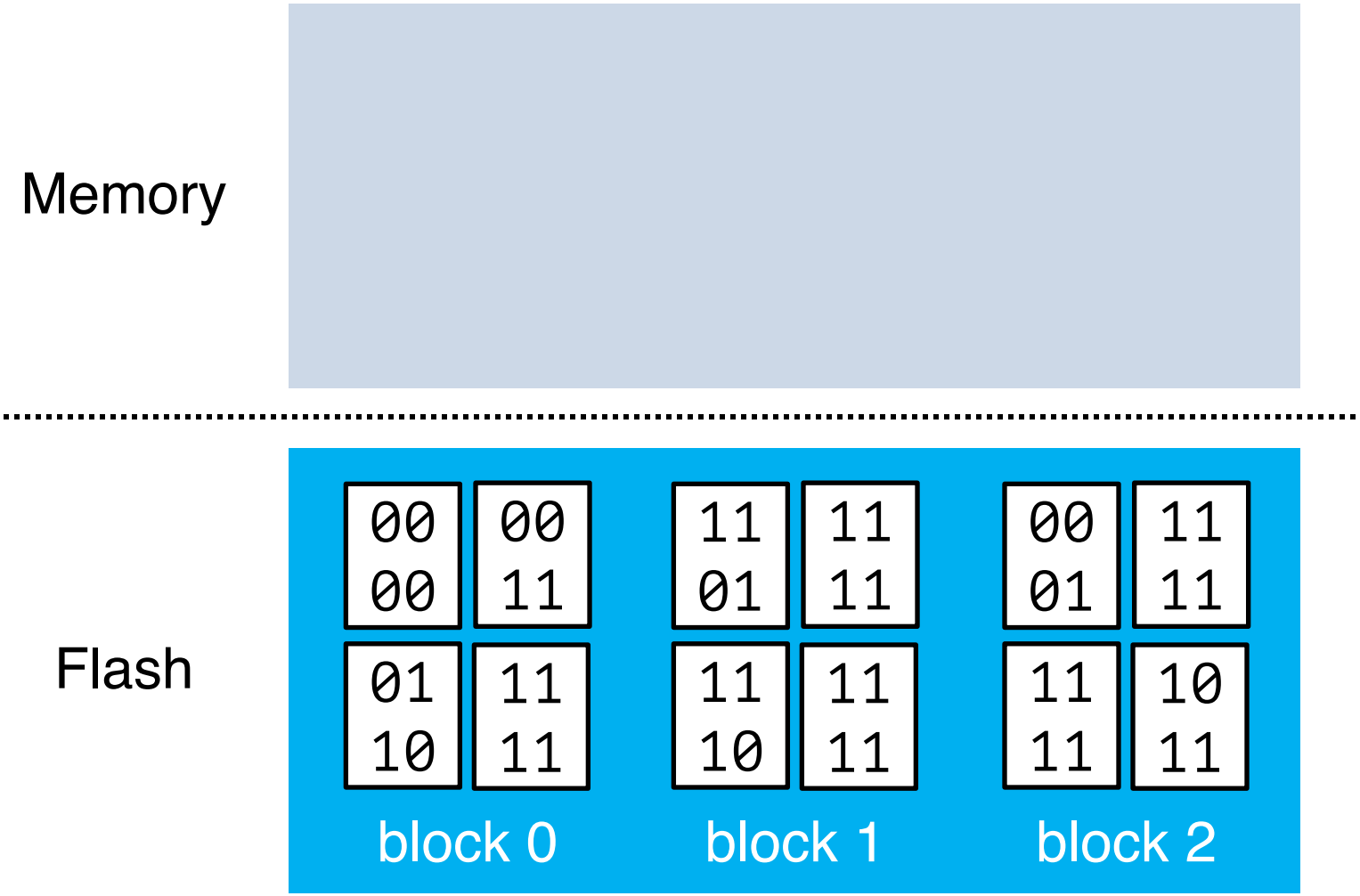

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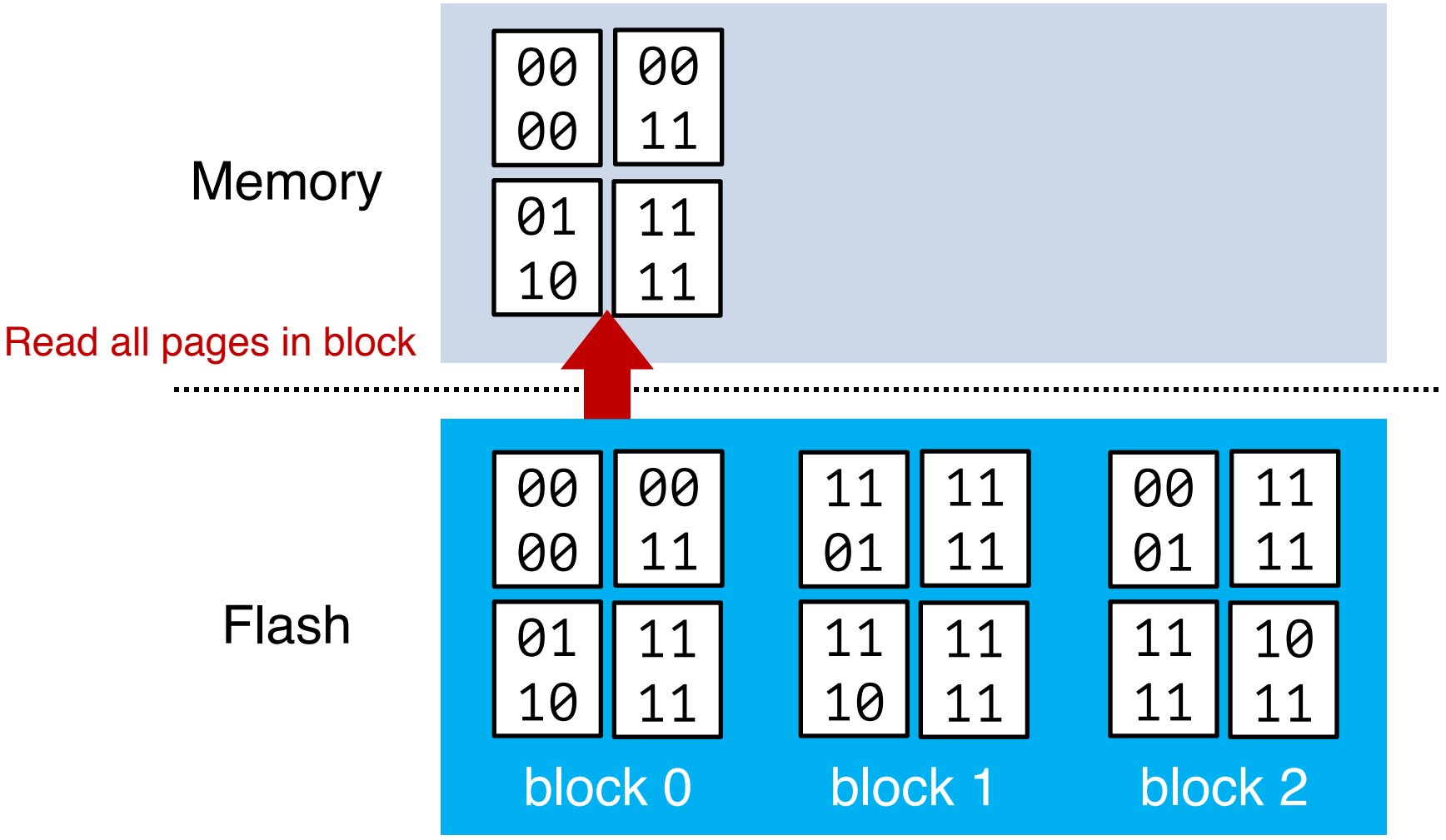

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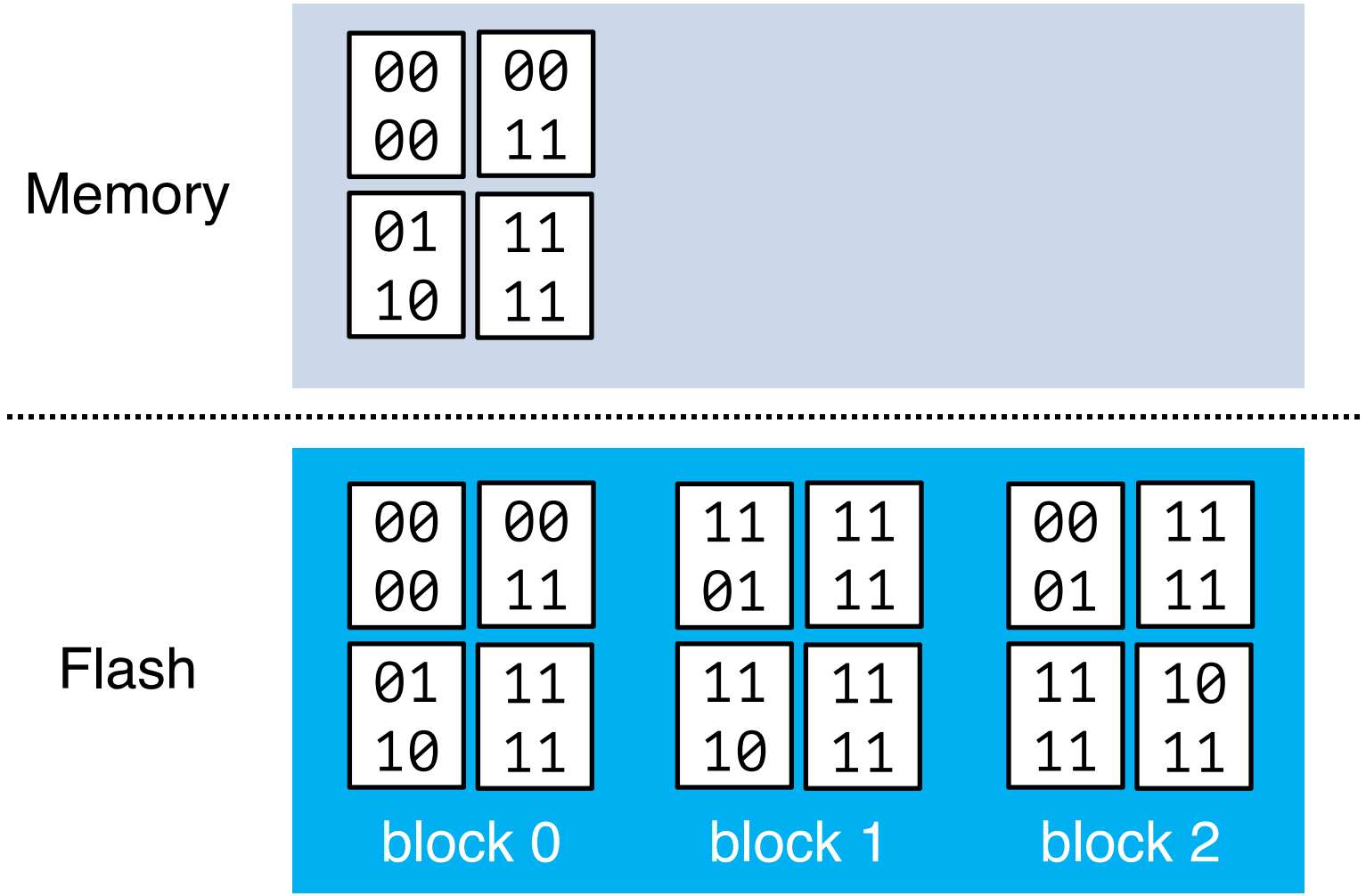
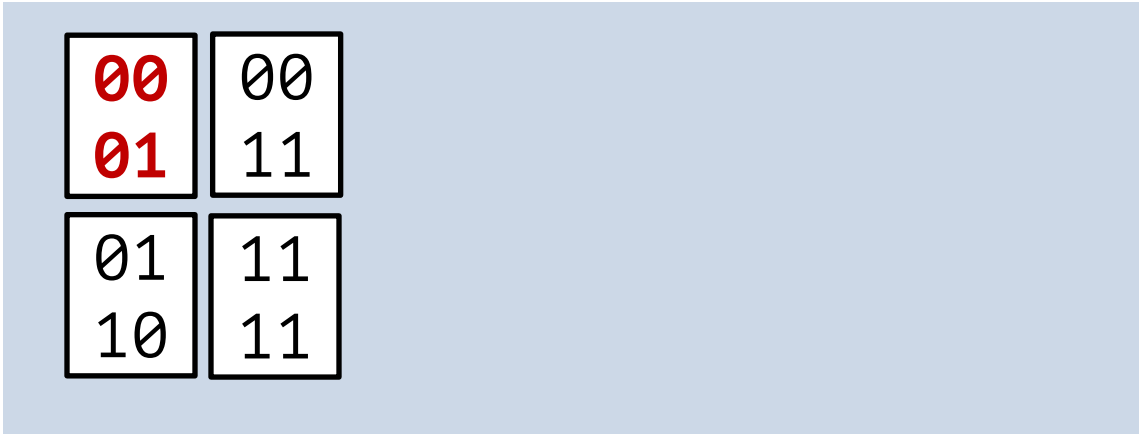


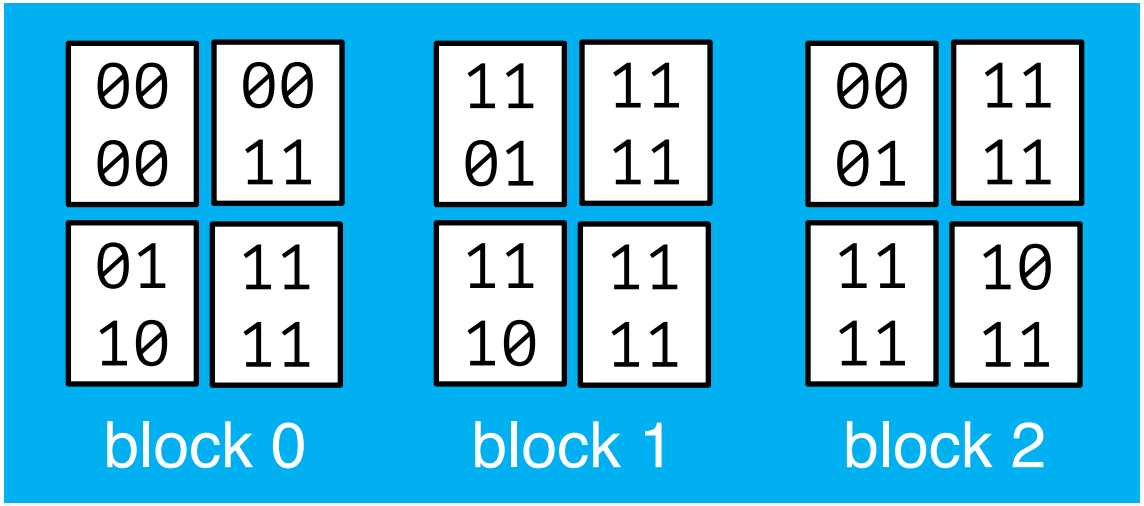
Awkward Flash Write

Modify target page in memory

Memory



Flash



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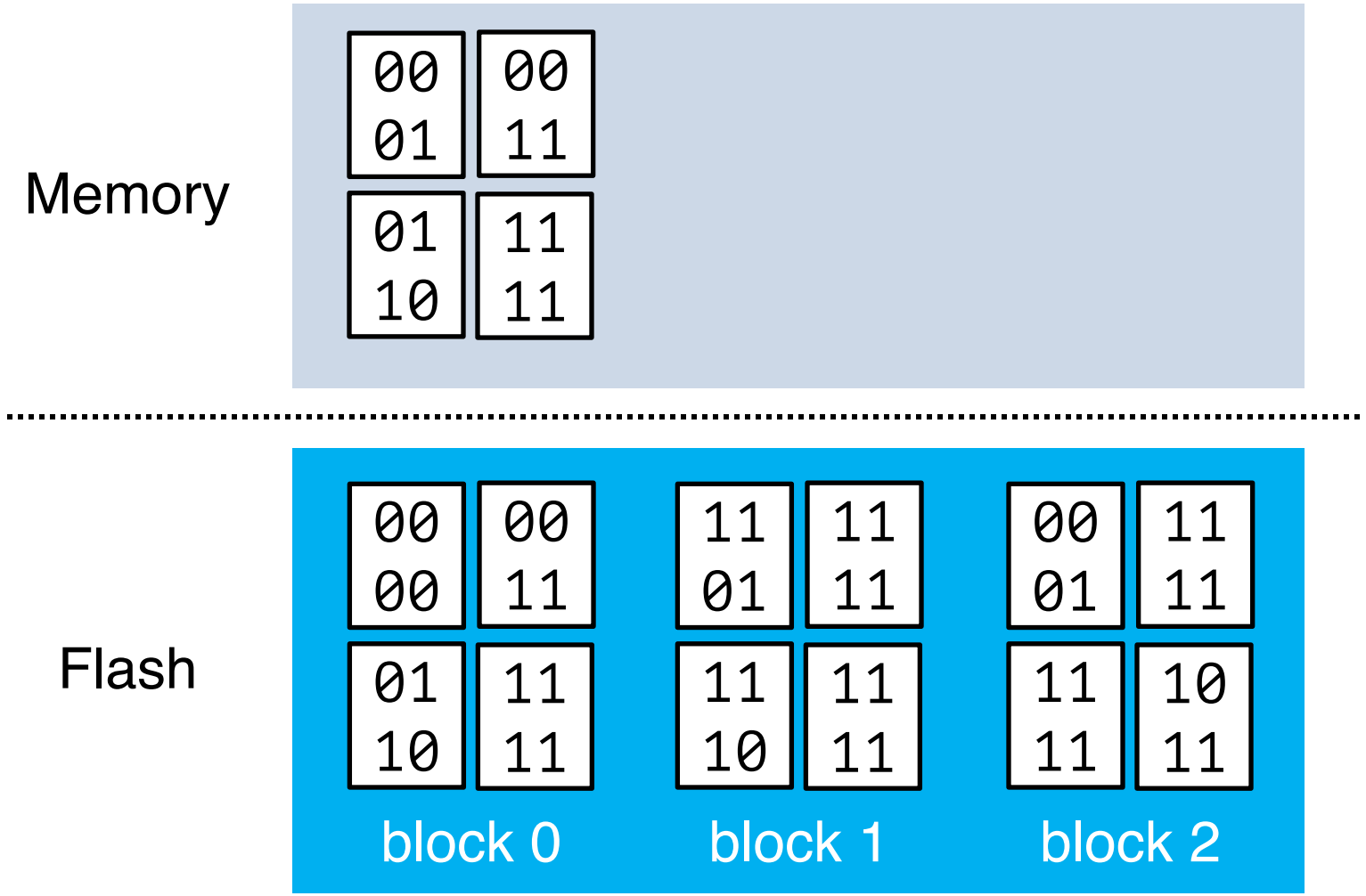

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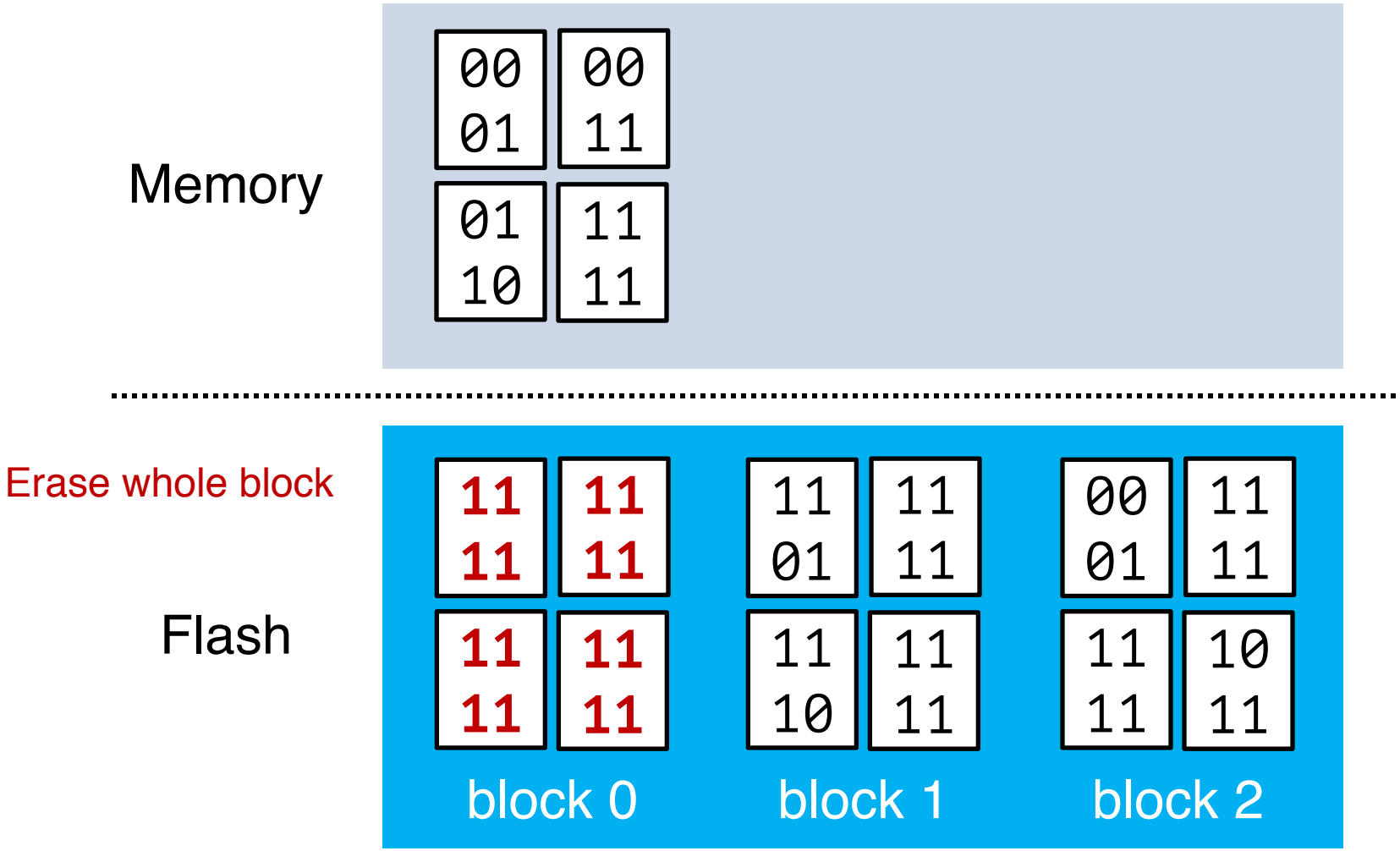

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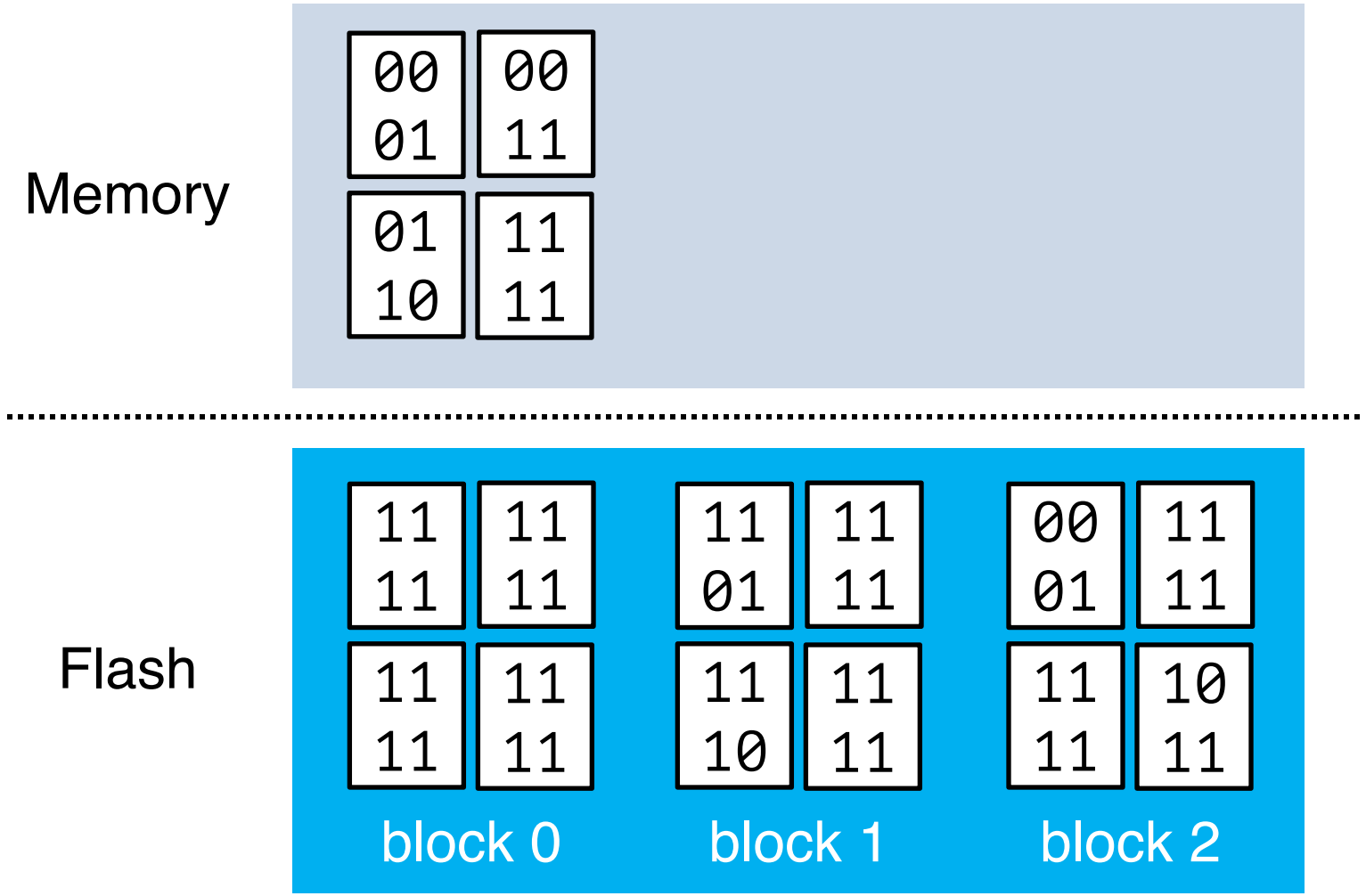

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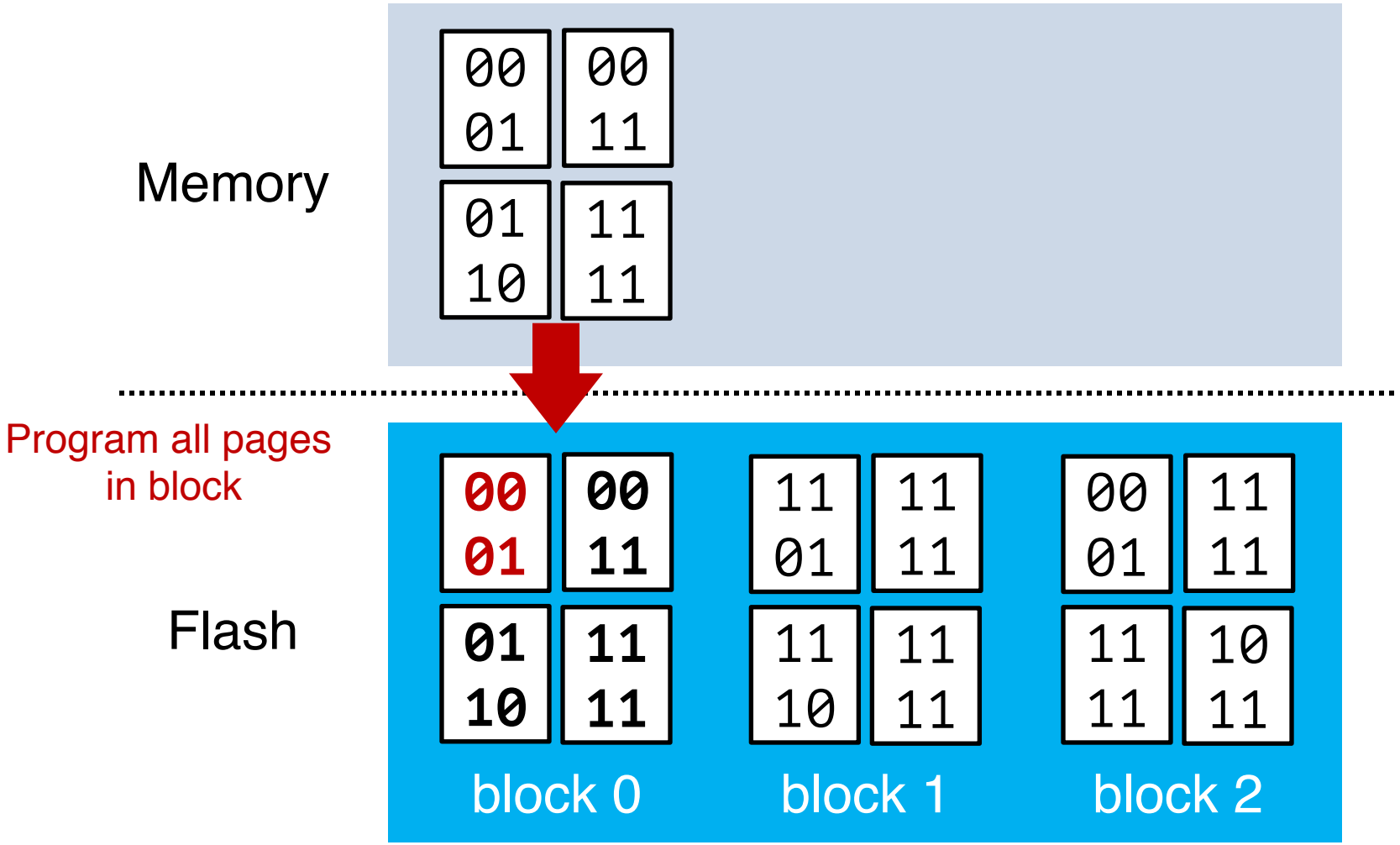

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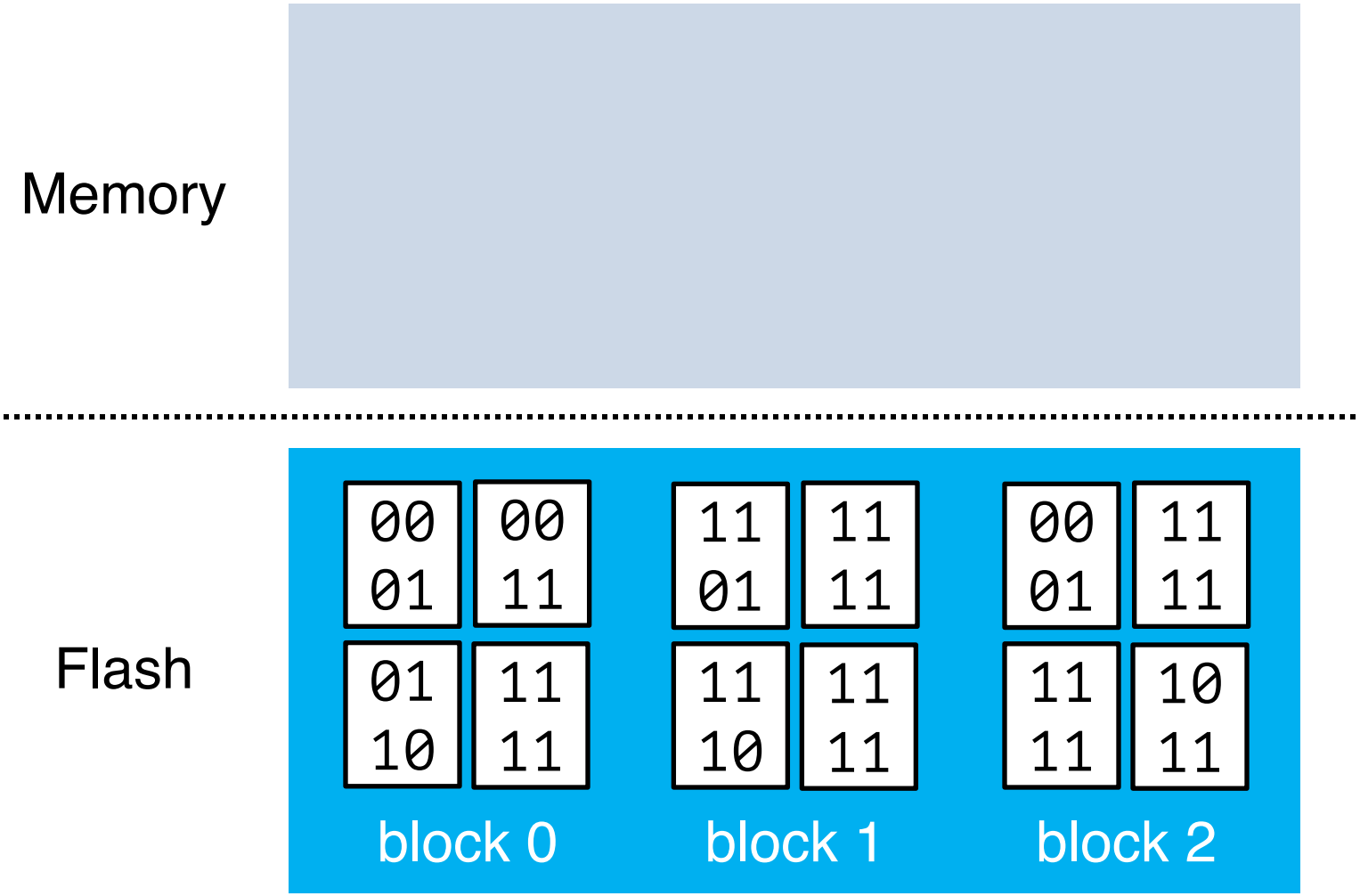


Issue: Write Amplification

- Random writes are expensive for flash!

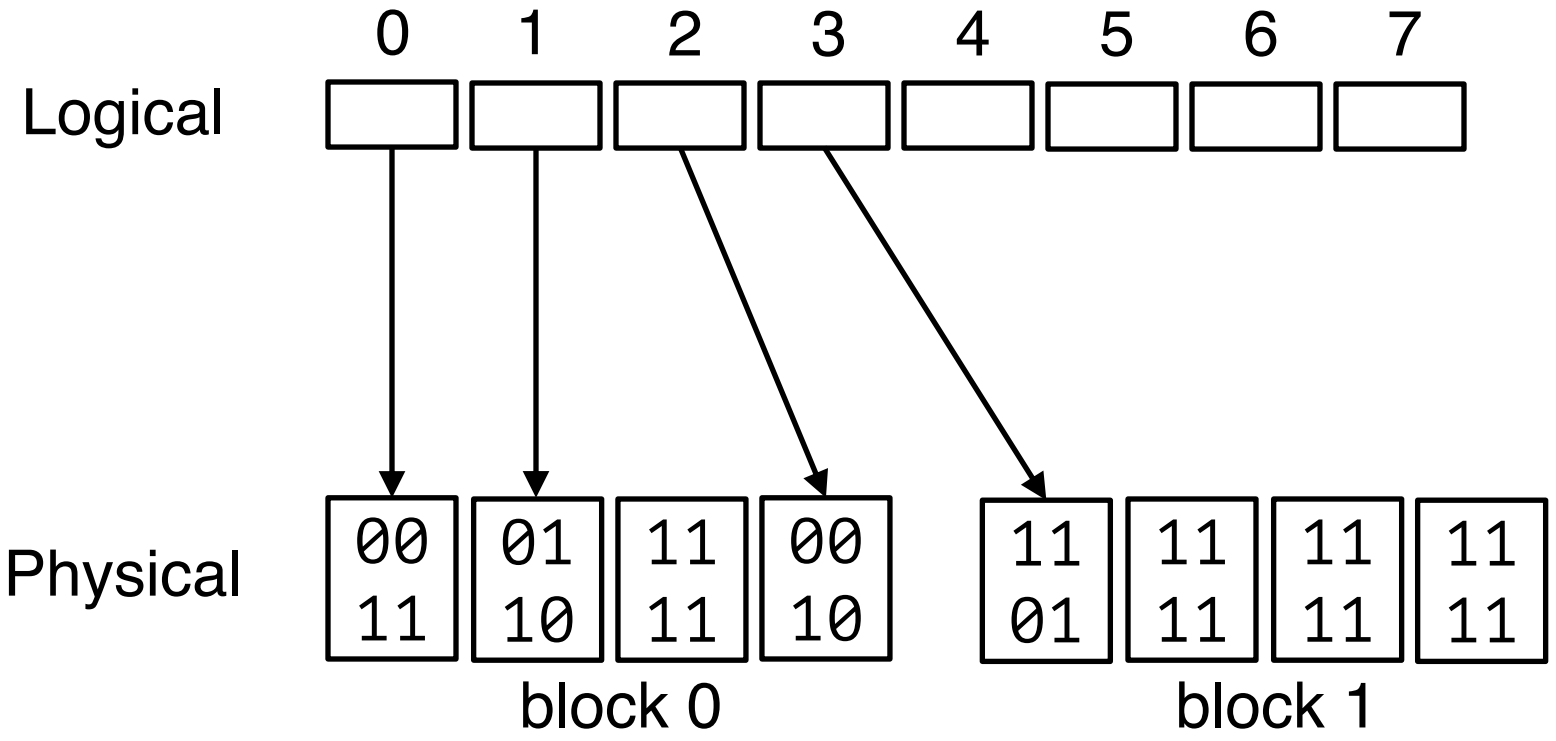
- Writing one 4KB page may cause:
  - `read`, `erase`, and `program` of the whole 256KB block

Flash Translation Layer

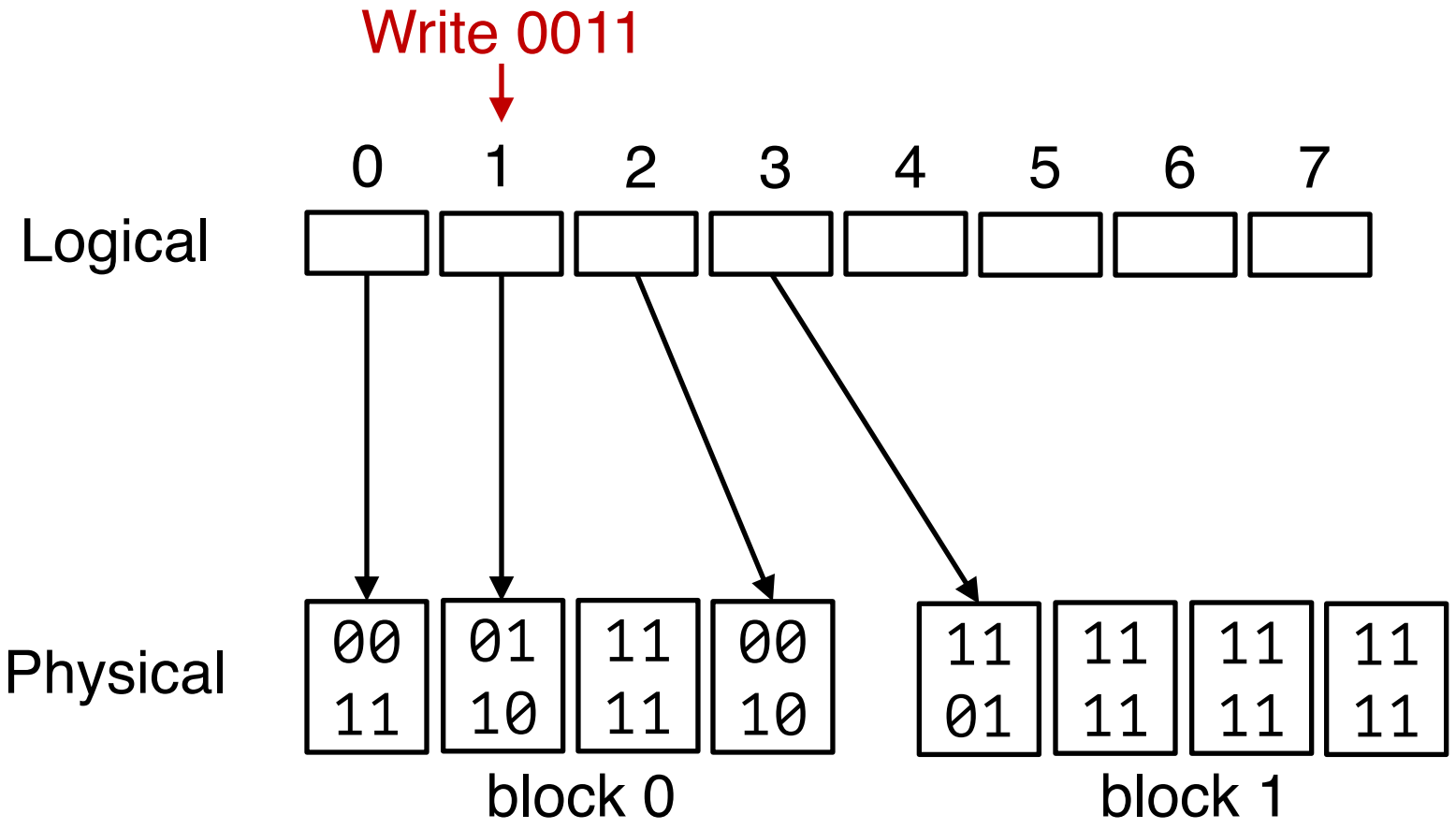
Flash Translation Layer (FTL)

- Add an address translation layer between upper-level file system and lower-level flash
  - Translate logical device addresses to physical addresses
  - Convert in-place write into append-write
  - Essentially, a **virtualization & optimization** layer

Flash Translation Layer (FTL)



Flash Translation Layer (FTL)



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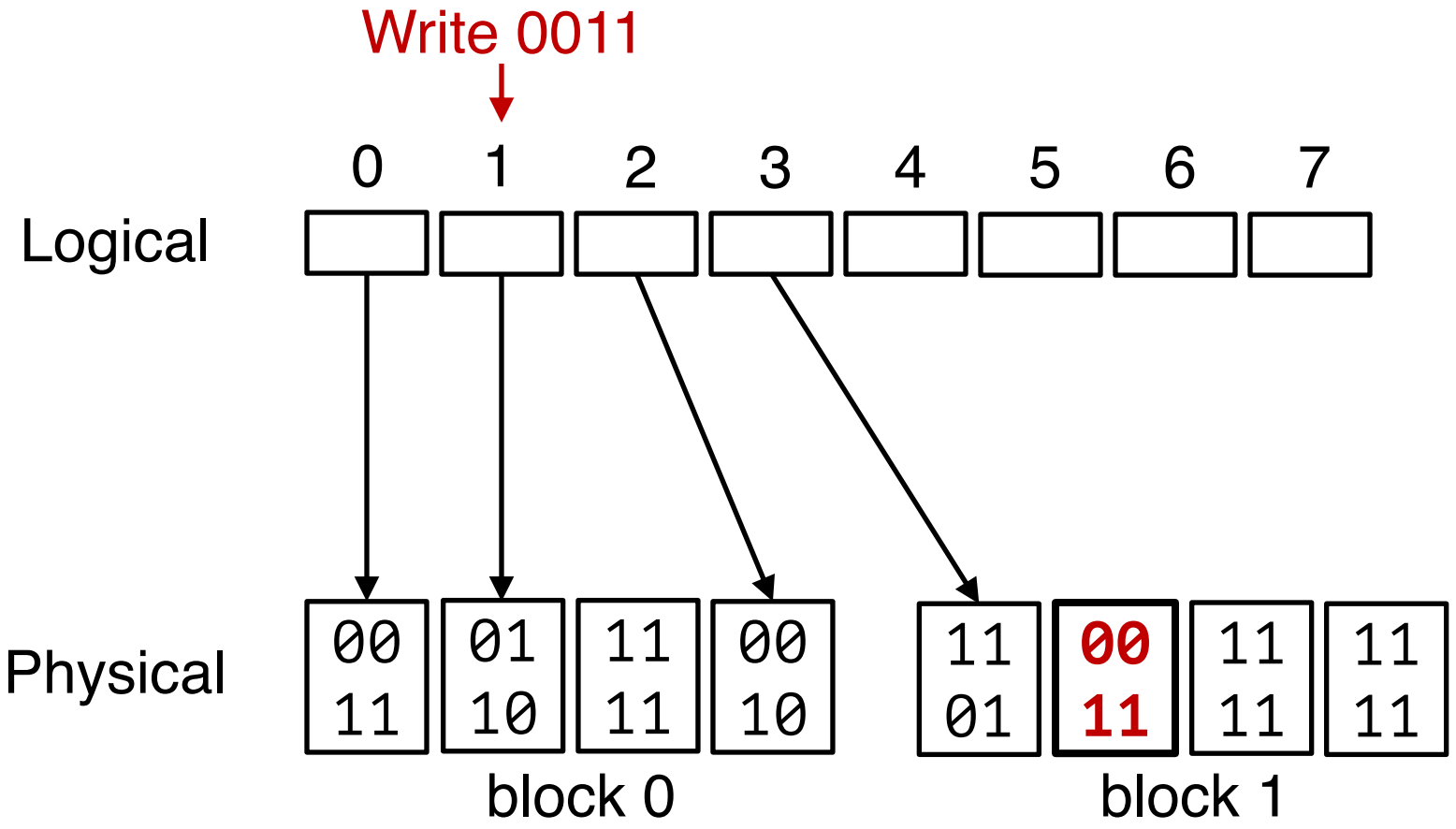

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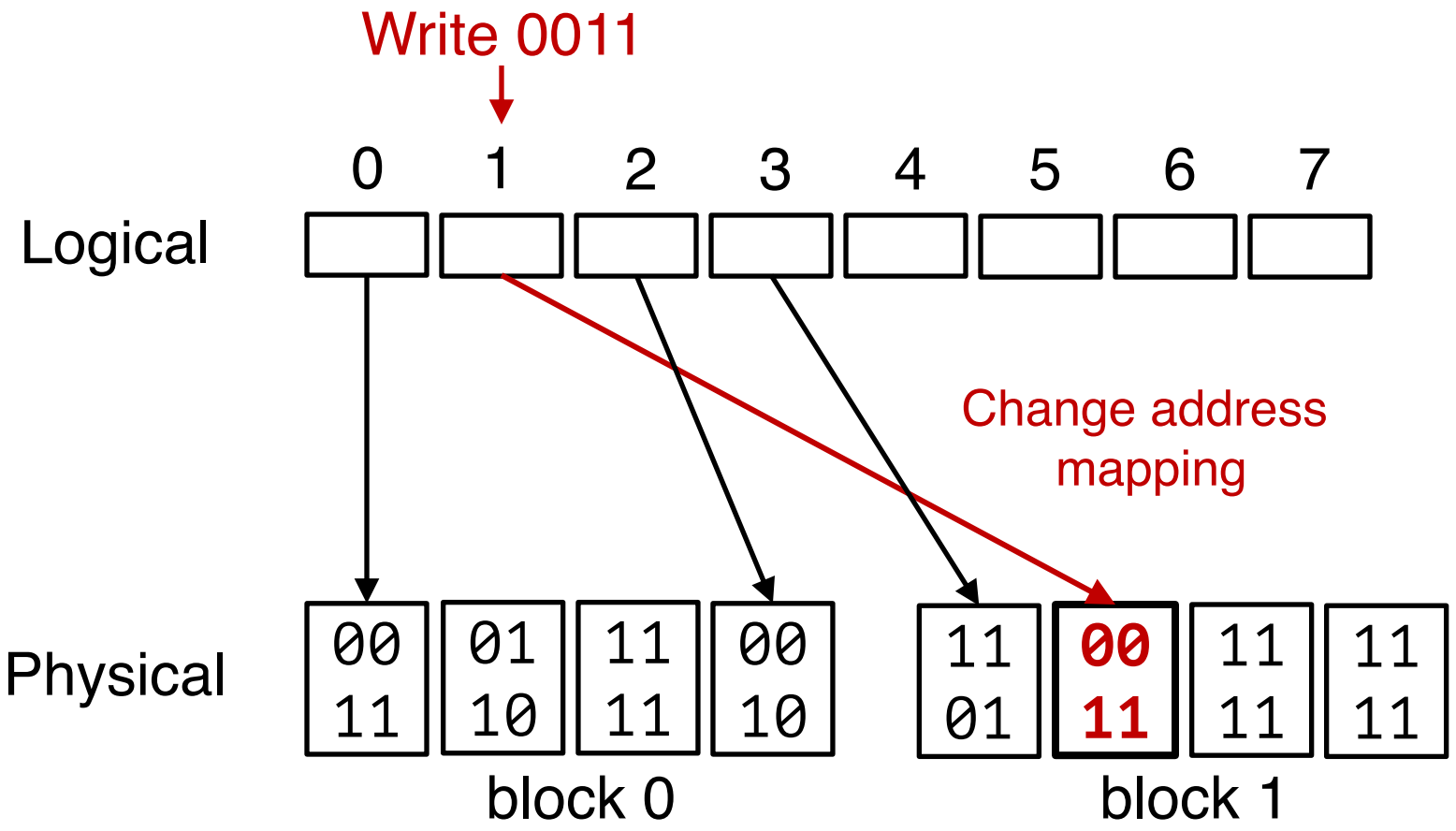

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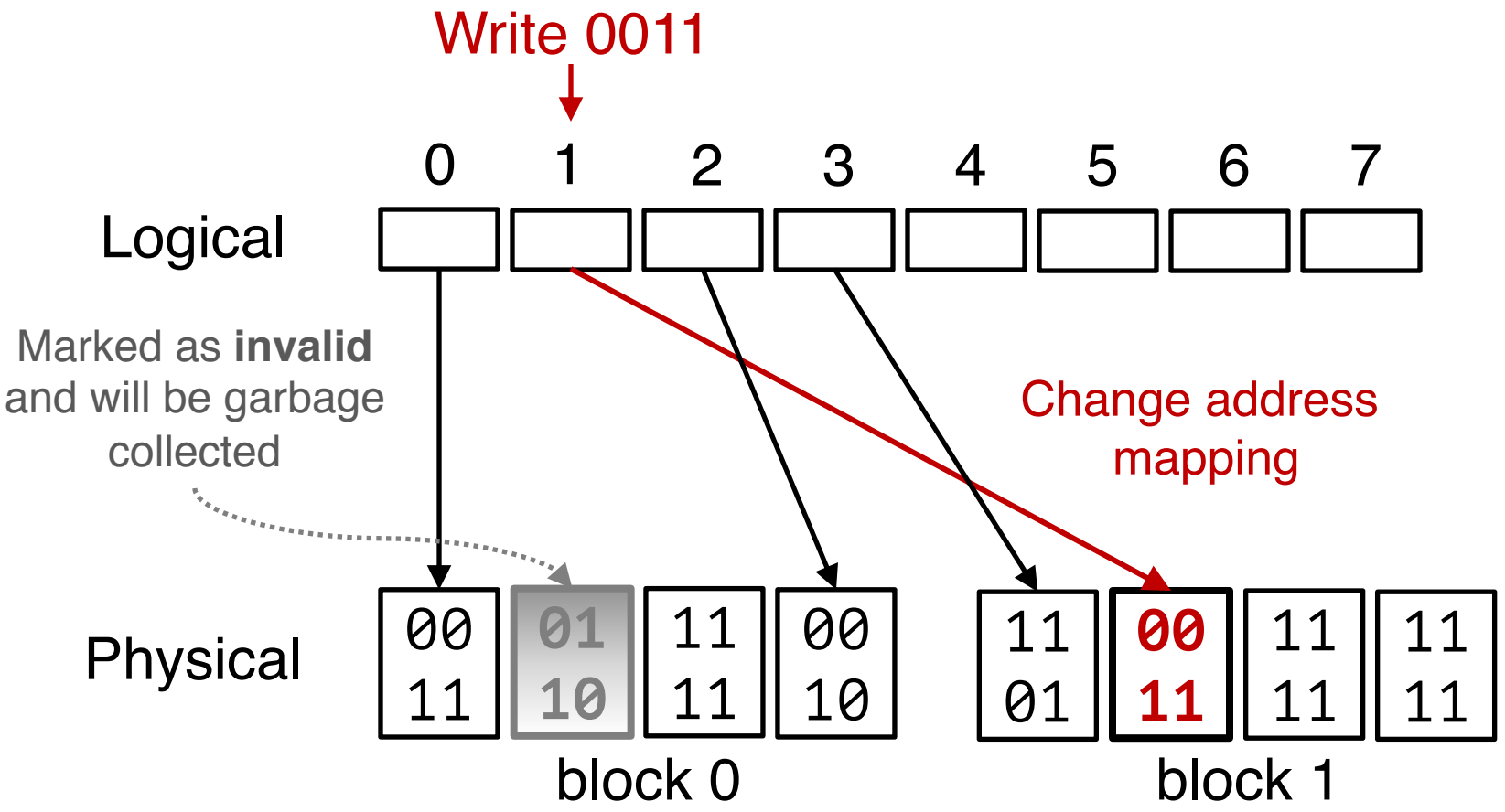
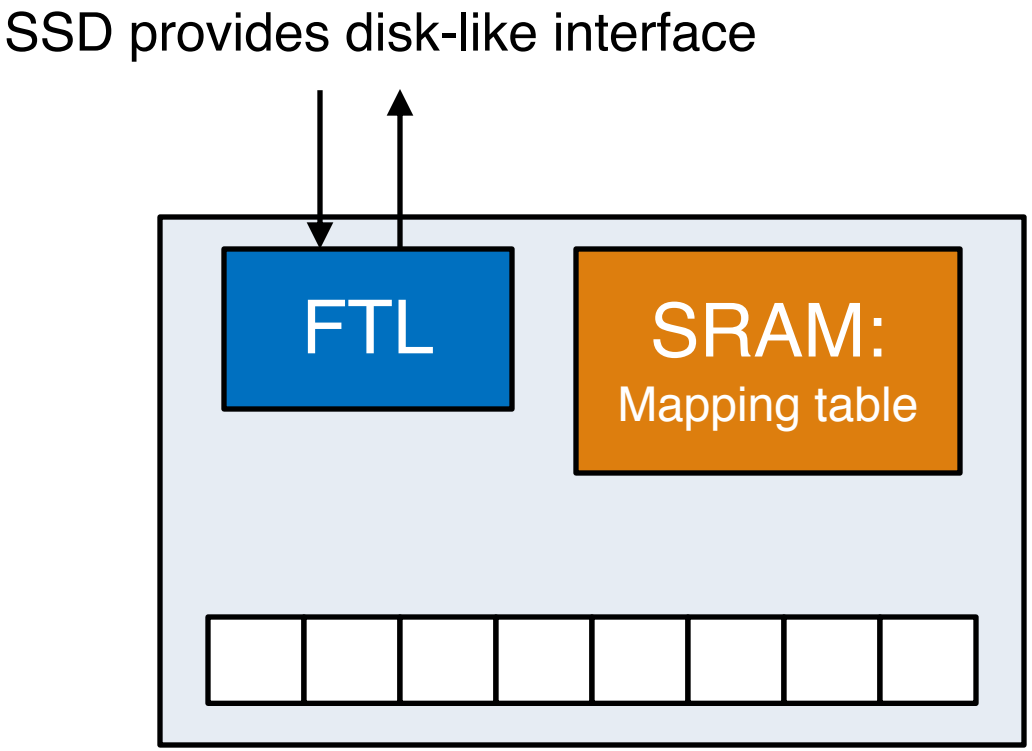


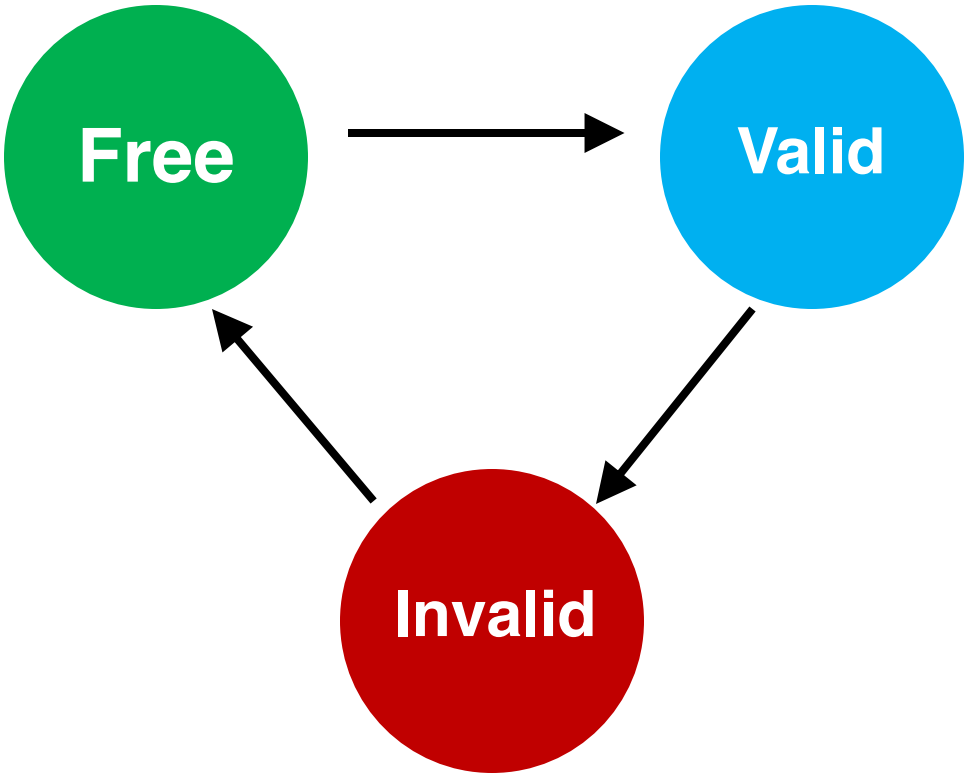
SSD Architecture with FTL



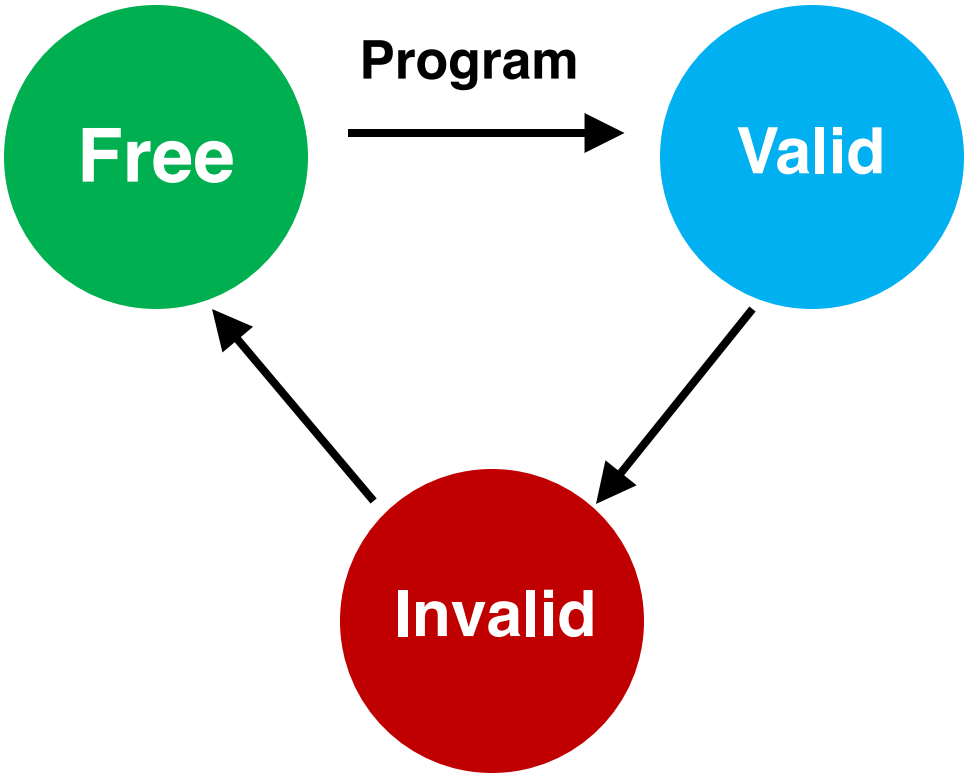
Flash Translation Layer (FTL)

- Usually implemented in flash device's firmware
- Where to store mapping?
  - SRAM
- Physical pages can be in three states
  - valid, invalid, free

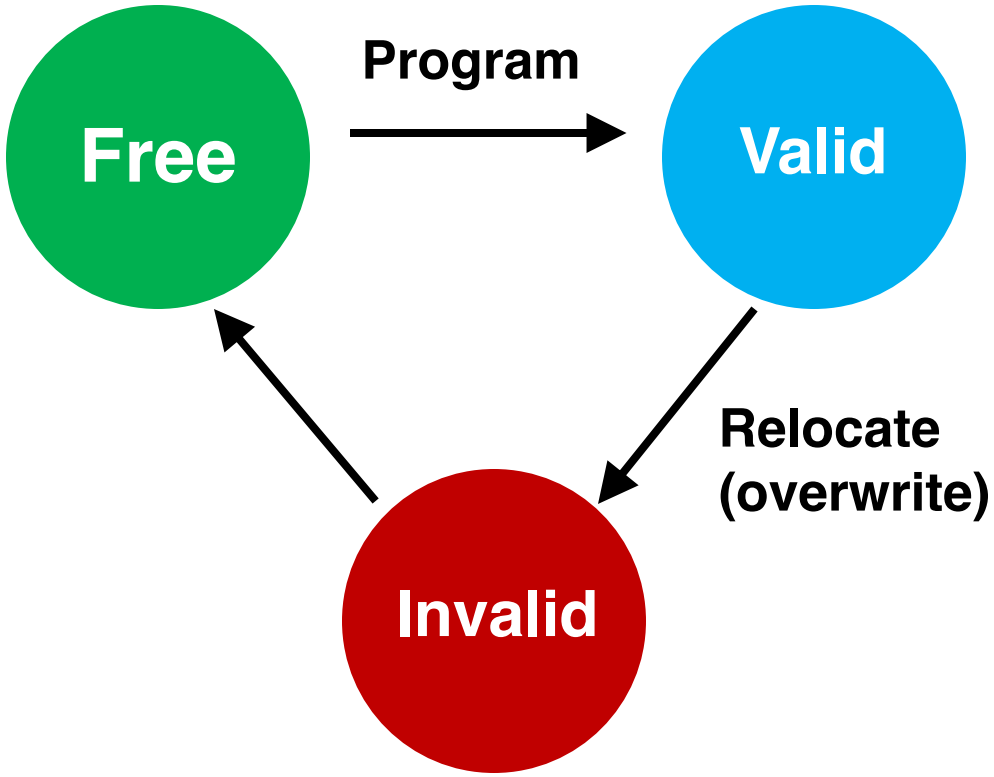
State Transition of Physical Pages



State Transition of Physical Pages



State Transition of Physical Pages



State Transition of Physical Pages