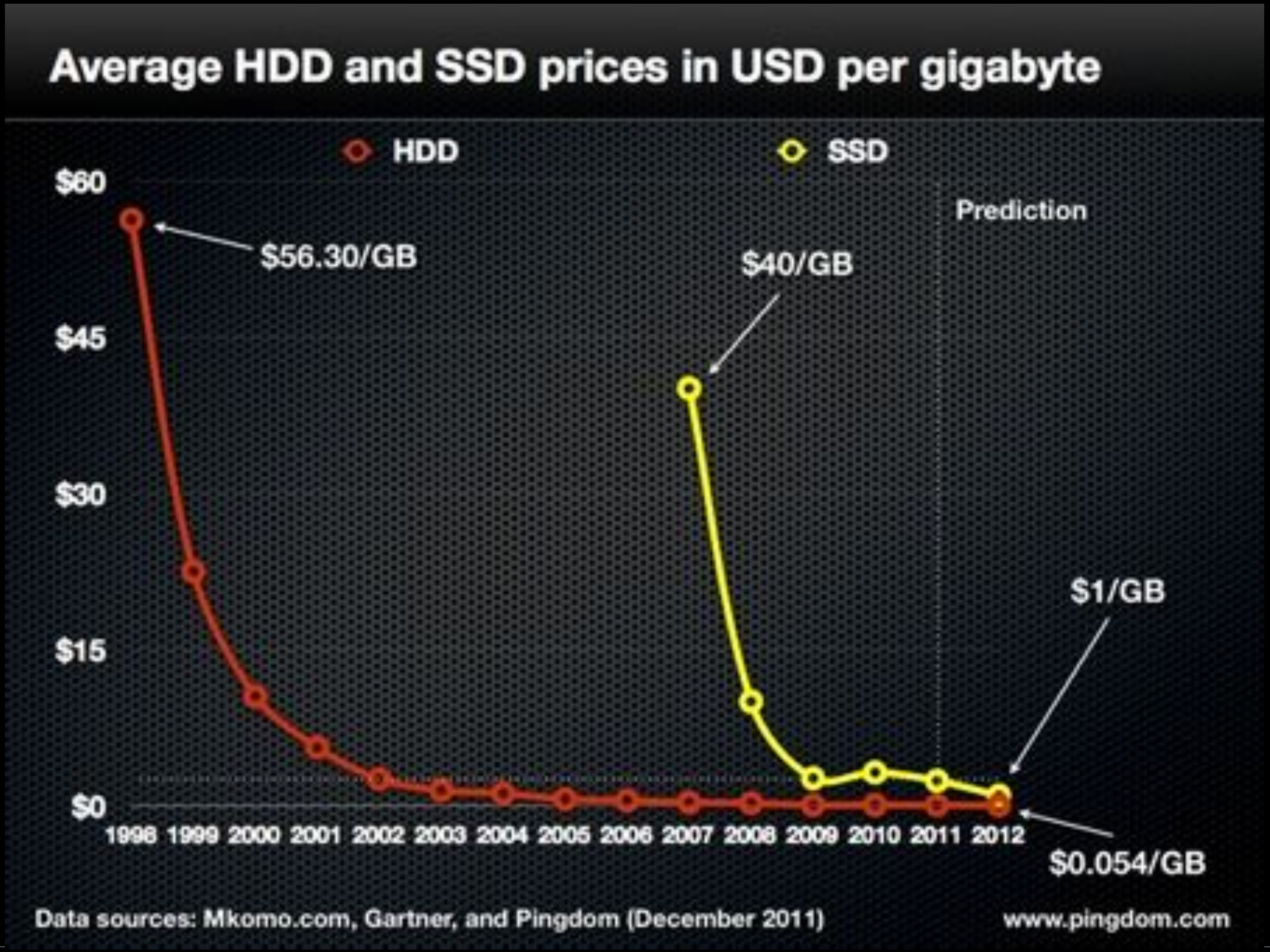
Flash-based SSDs

[Material based on slides from Tyler Caraza-Harter]
www: https://tyler.caraza-harter.com

SSDs vs. HDDs

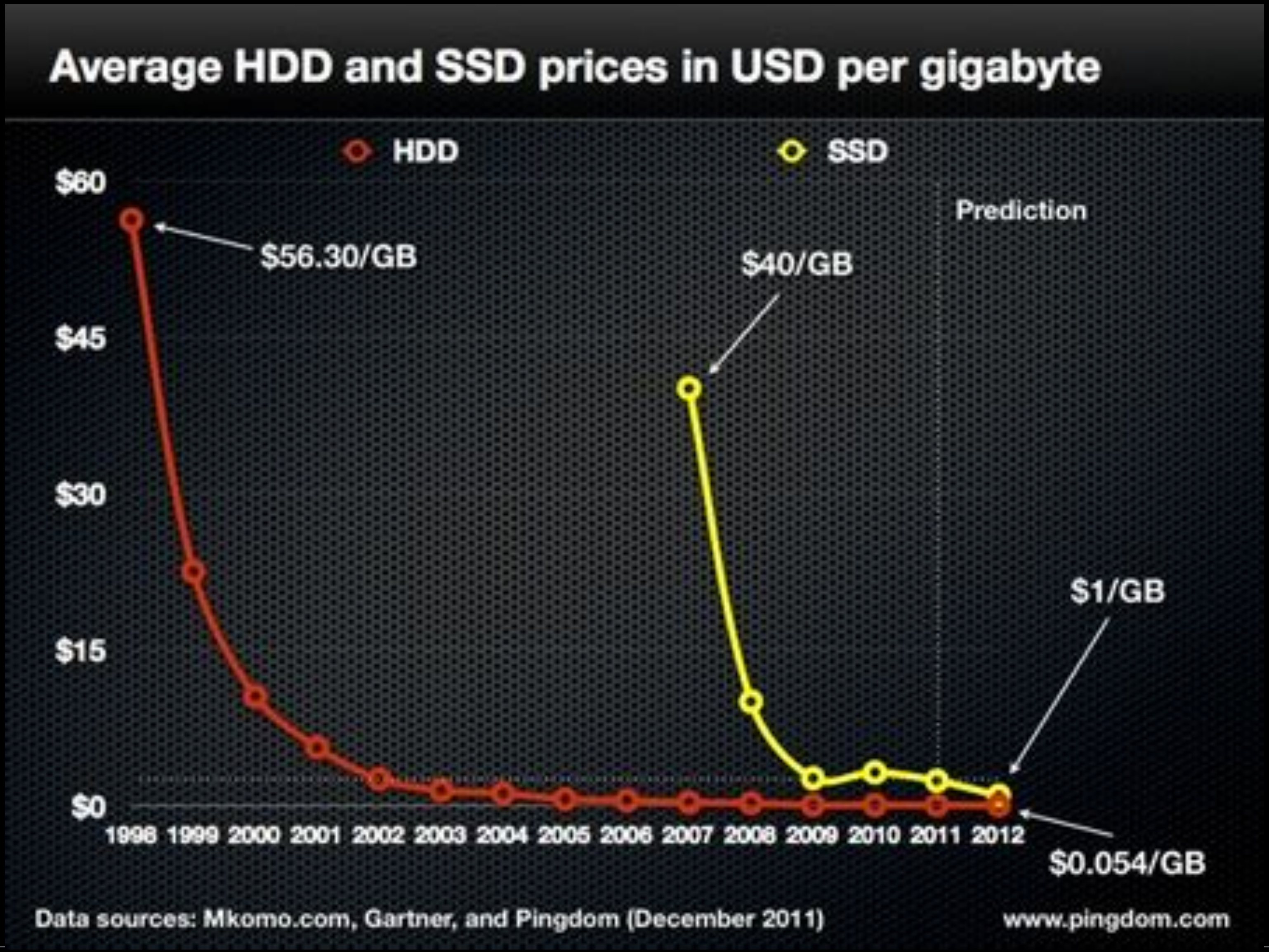
Dimension 1: Cost

Cost: HDD vs. SSD



Source: http://www.tomshardware.com/news/ssd-hdd-solid-state-drive-hard-disk-drive-prices,14336.html

Cost: HDD vs. SSD



Note: These are trends, not the most up-to-date data.

There are different classes of HDDs and SSDs which complicate this graph, but the thing to note is that there is a gap, but it is narrowing and all costs are trending downward.

Source: http://www.tomshardware.com/news/ssd-hdd-solid-state-drive-hard-disk-drive-prices,14336.html

SSDs vs. HDDs

Dimension 1: Cost

Dimension 2: Physical Media

Disk Overview

I/O cost: **setup** (seek + rotate), **transfer**

Implications:
- cannot parallelize operations (only one head)
- slow (mechanical parts must move through space)
- poor random I/O (locality around disk head)

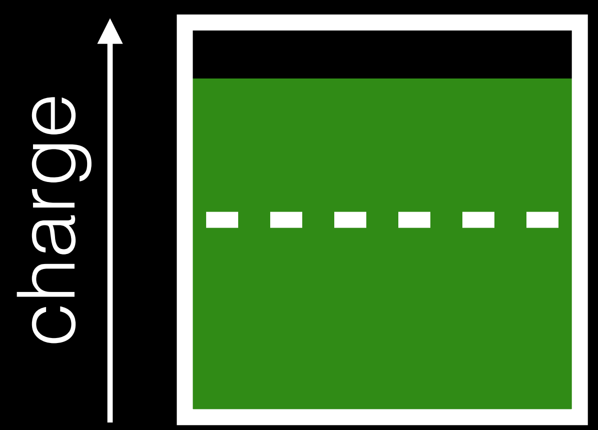
Random I/Os take 10ms+!

Flash

No moving parts! Instead, SSDs:

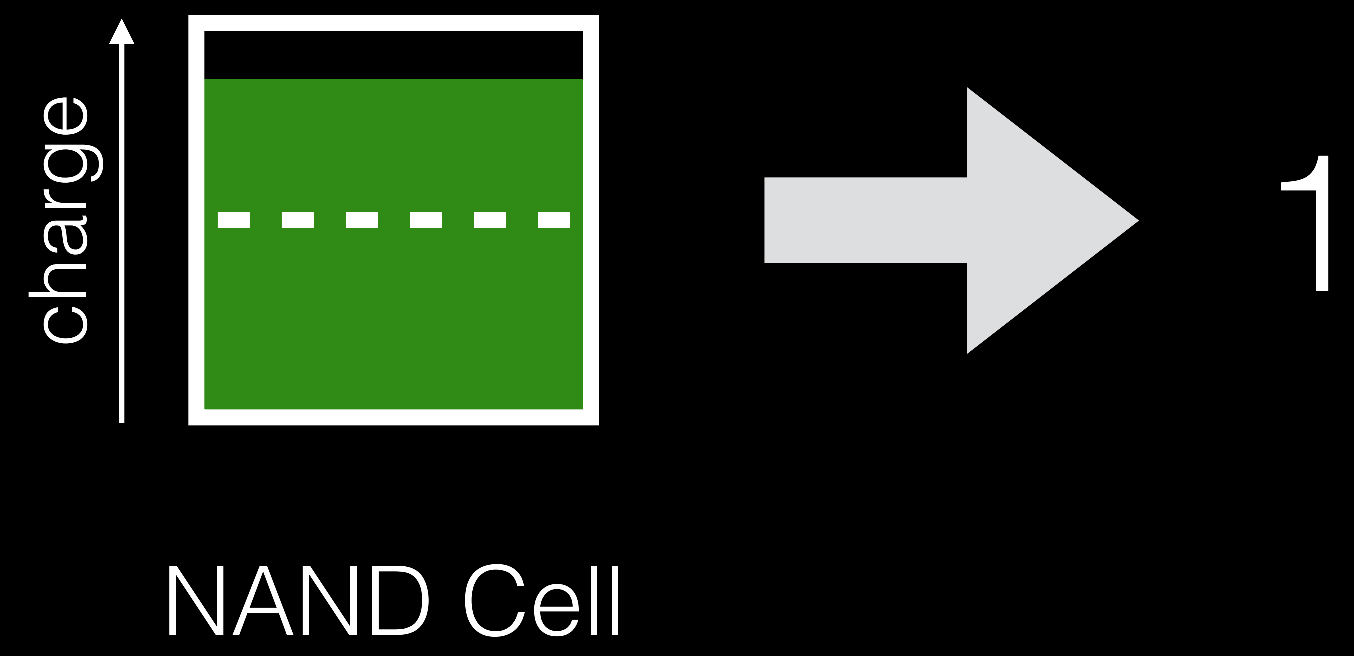
- Hold charge in **cells**
  - **No seeks in I/O setup!**
- Hardware organization supports **internal parallelism**.

SLC: Single-Level Cell

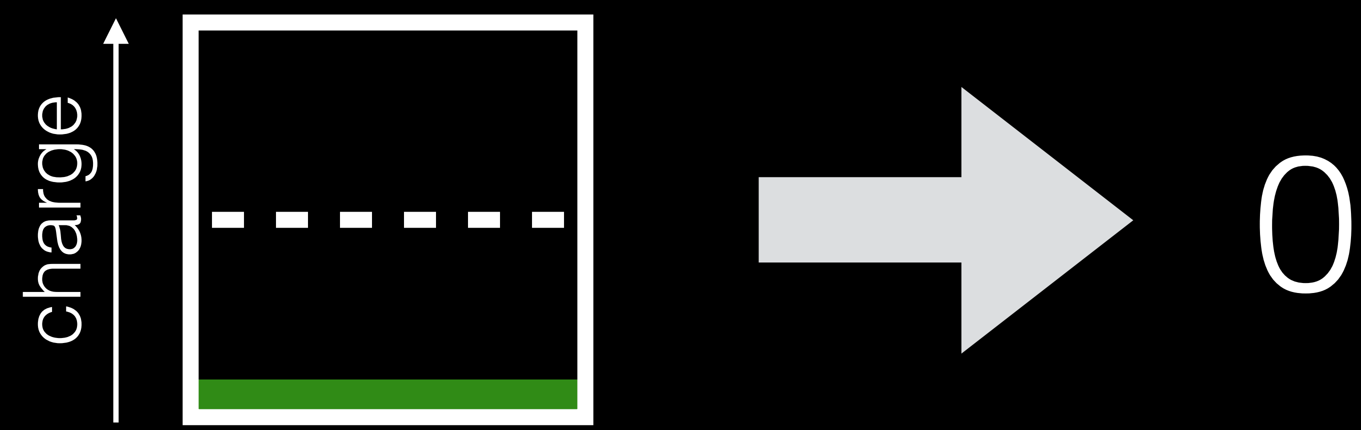


NAND Cell

SLC: Single-Level Cell

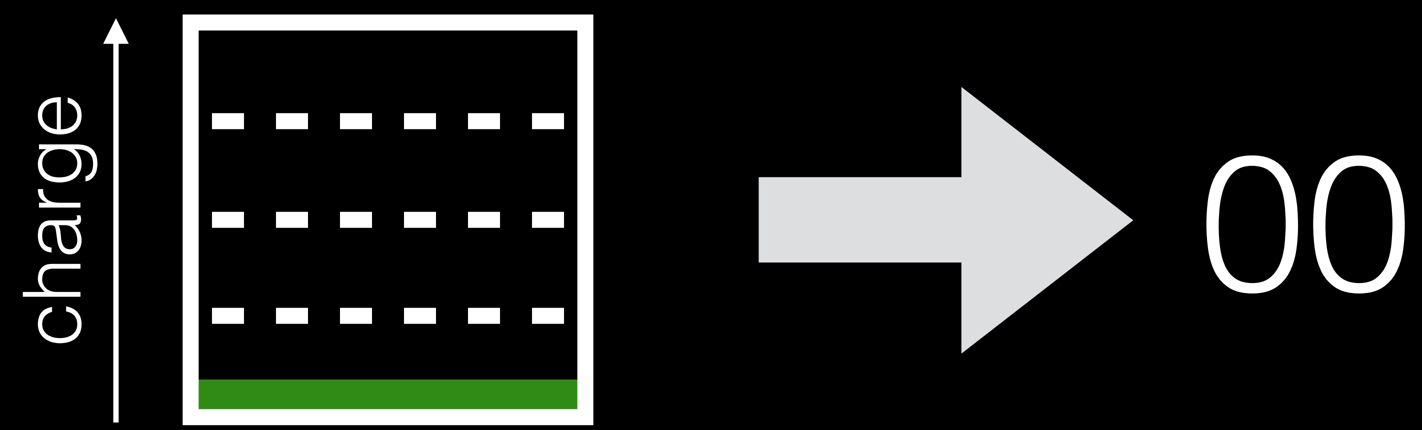


SLC: Single-Level Cell



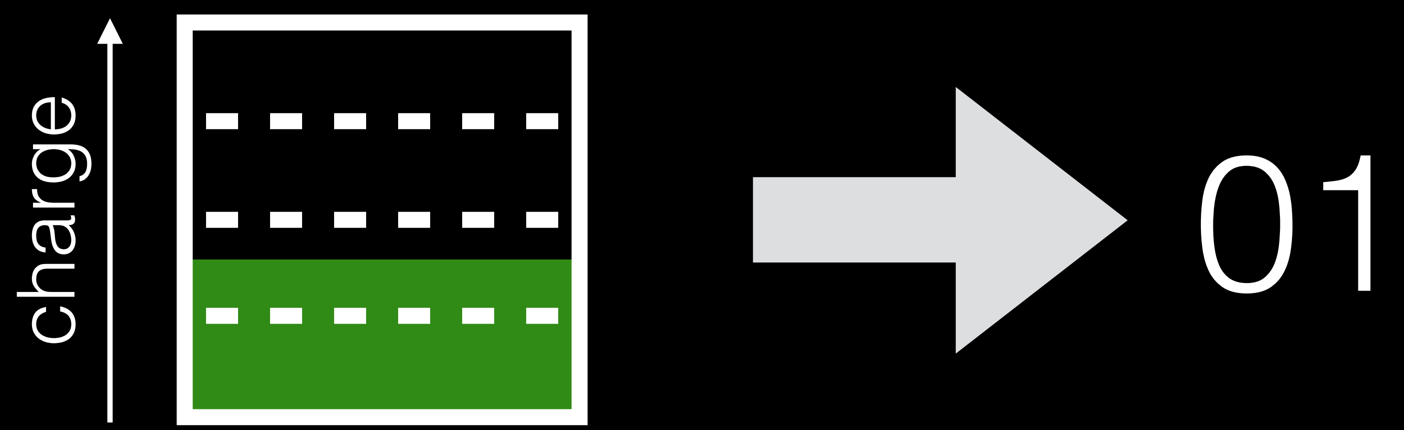
NAND Cell

MLC: Multi-Level Cell



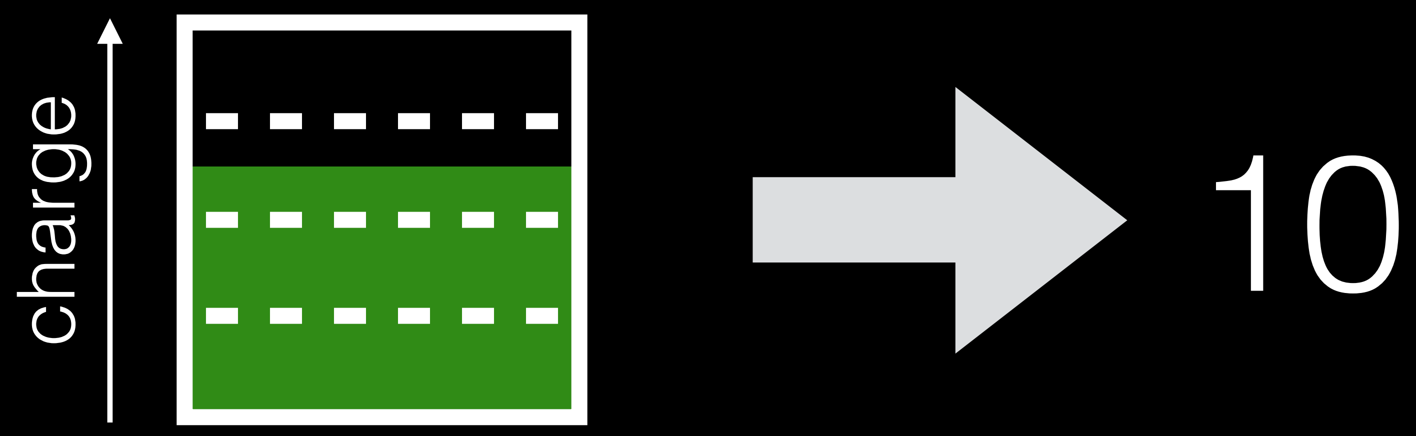
NAND Cell

MLC: Multi-Level Cell



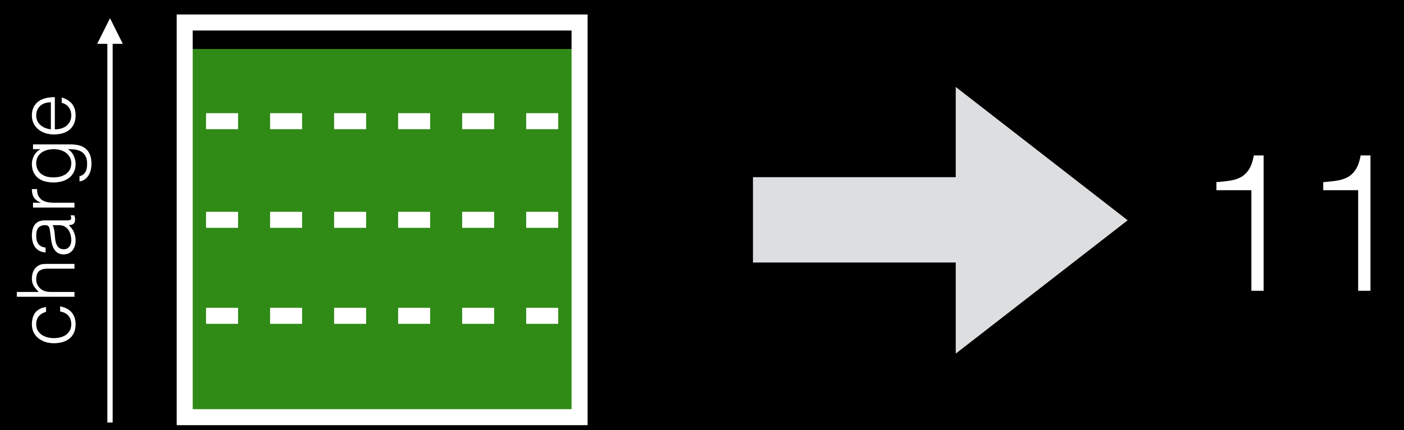
NAND Cell

MLC: Multi-Level Cell



NAND Cell

MLC: Multi-Level Cell

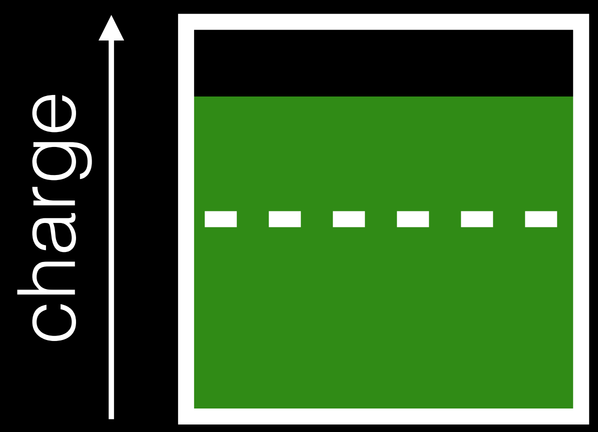


NAND Cell

Single- vs. Multi- Level Cell

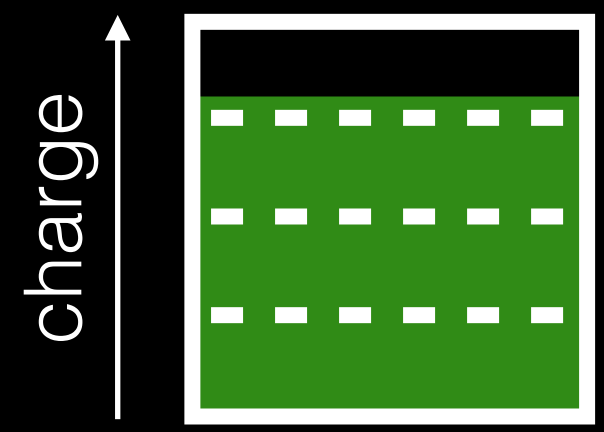
Single- vs. **M**ulti- **L**evel **C**ell

SLC



expensive
robust

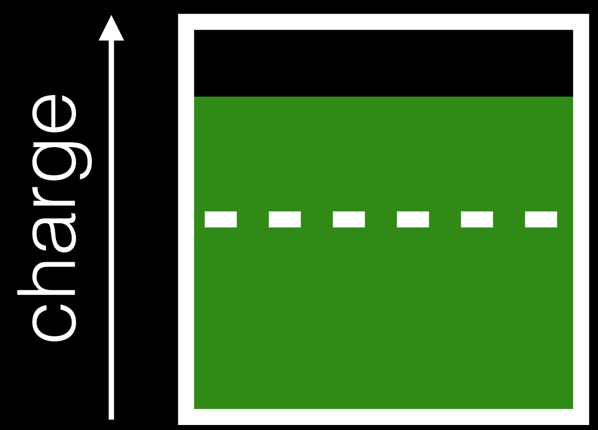
MLC



cheap
sensitive

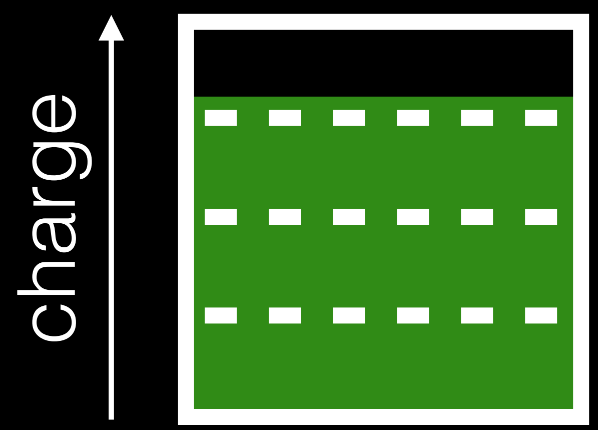
Single- vs. **M**ulti- **L**evel **C**ell

SLC



expensive
robust

MLC



cheap
sensitive

TLC (3 bits/cell) and QLC (4 bits/cell) also exist, and are even cheaper and more sensitve than MLC.

SSDs vs. HDDs

Dimension 1: Cost

Dimension 2: Physical Media

Dimension 3: Lifetime

Wearout

Problem: flash cells wear out after being overwritten too many times.

MLC: ~10K writes
SLC: ~100K writes

Wearout

Problem: flash cells wear out after being overwritten too many times.

MLC: ~10K writes
SLC: ~100K writes

Cell management strategy: wear leveling.

- Distribute writes across cells to more evenly spread the wear
    - Prevents some cells from wearing out while others still fresh.

SSDs vs. HDDs

Dimension 1: Cost

Dimension 2: Physical Media

Dimension 3: Lifetime

Dimension 4: Internal Organization

Banks

Flash chips are divided into banks (aka, planes).

Banks can be accessed in parallel.

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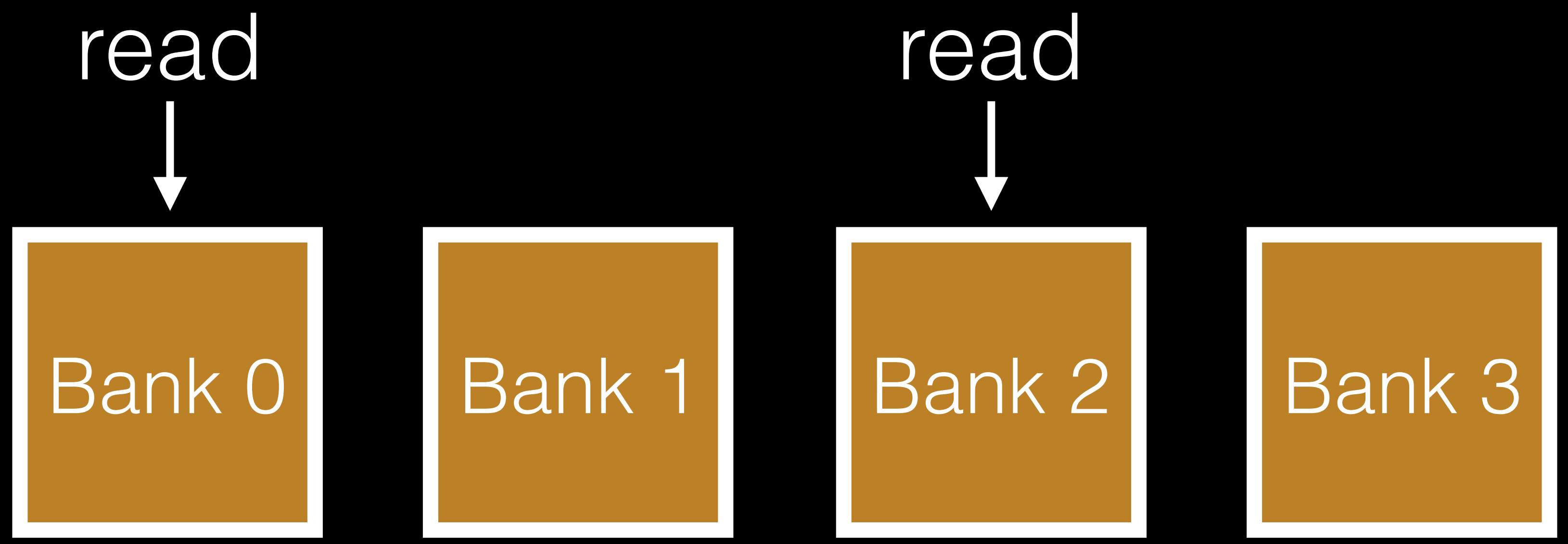

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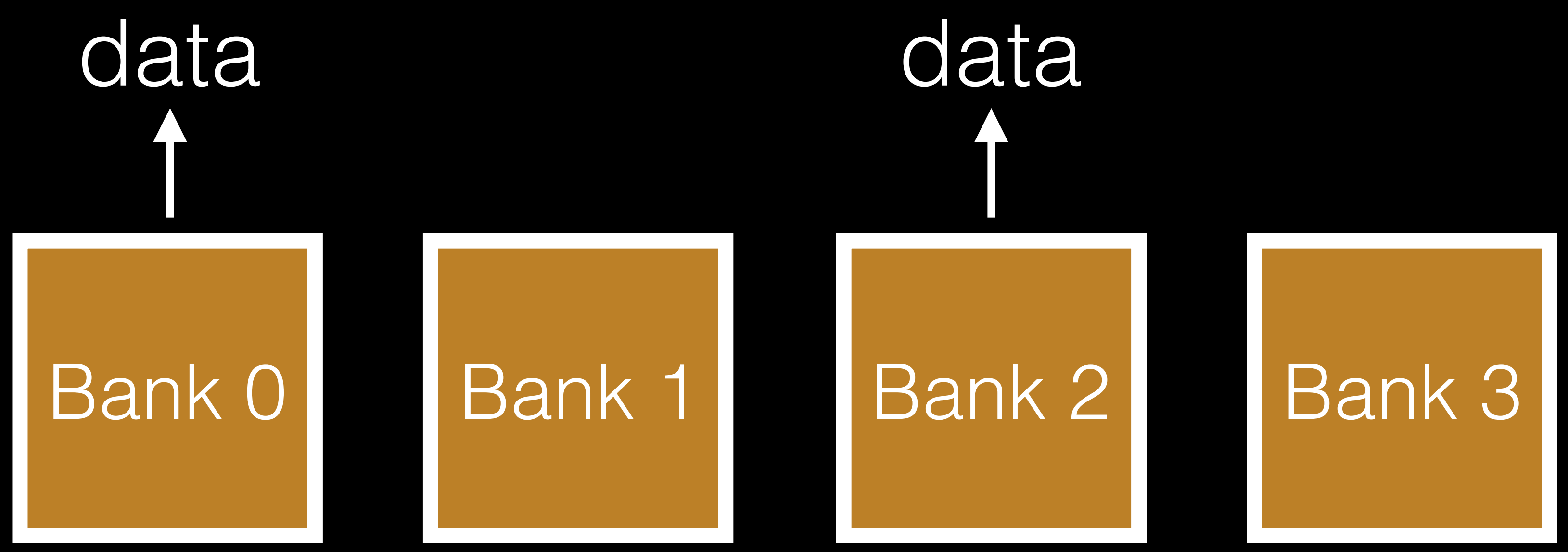


Banks

Flash chips are divided into banks (aka, planes).

Banks can be accessed in parallel.

Flash Writes

Writing 0's:
- fast, fine-grained

Writing 1's:
- slow, course-grained

Flash Writes

Writing 0’s:
- fast, fine-grained
- called “program”

Writing 1’s:
- slow, course-grained
- called “erase”

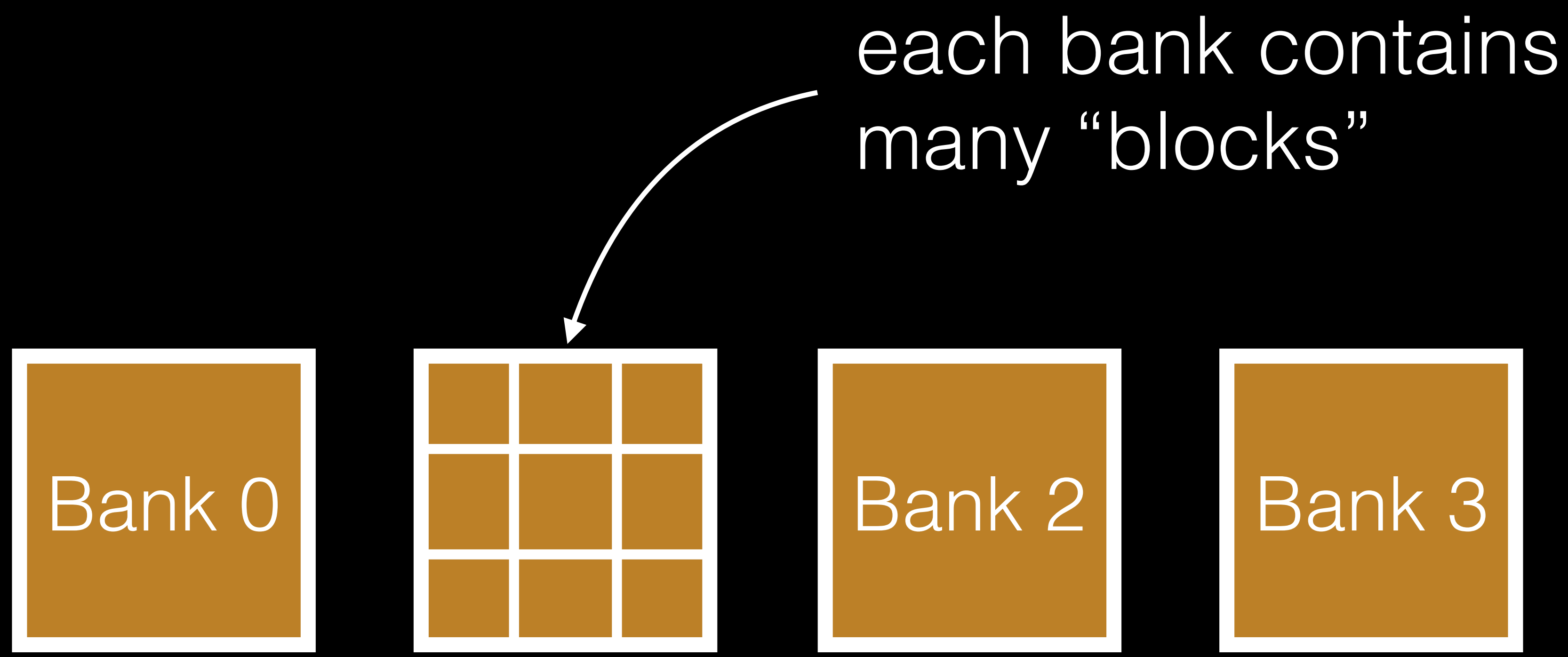
Flash Writes

Writing 0’s:
 - fast, fine-grained [unit: **page**]
 - called “program”

Writing 1’s:
 - slow, course-grained [unit: **block**]
 - called “erase”

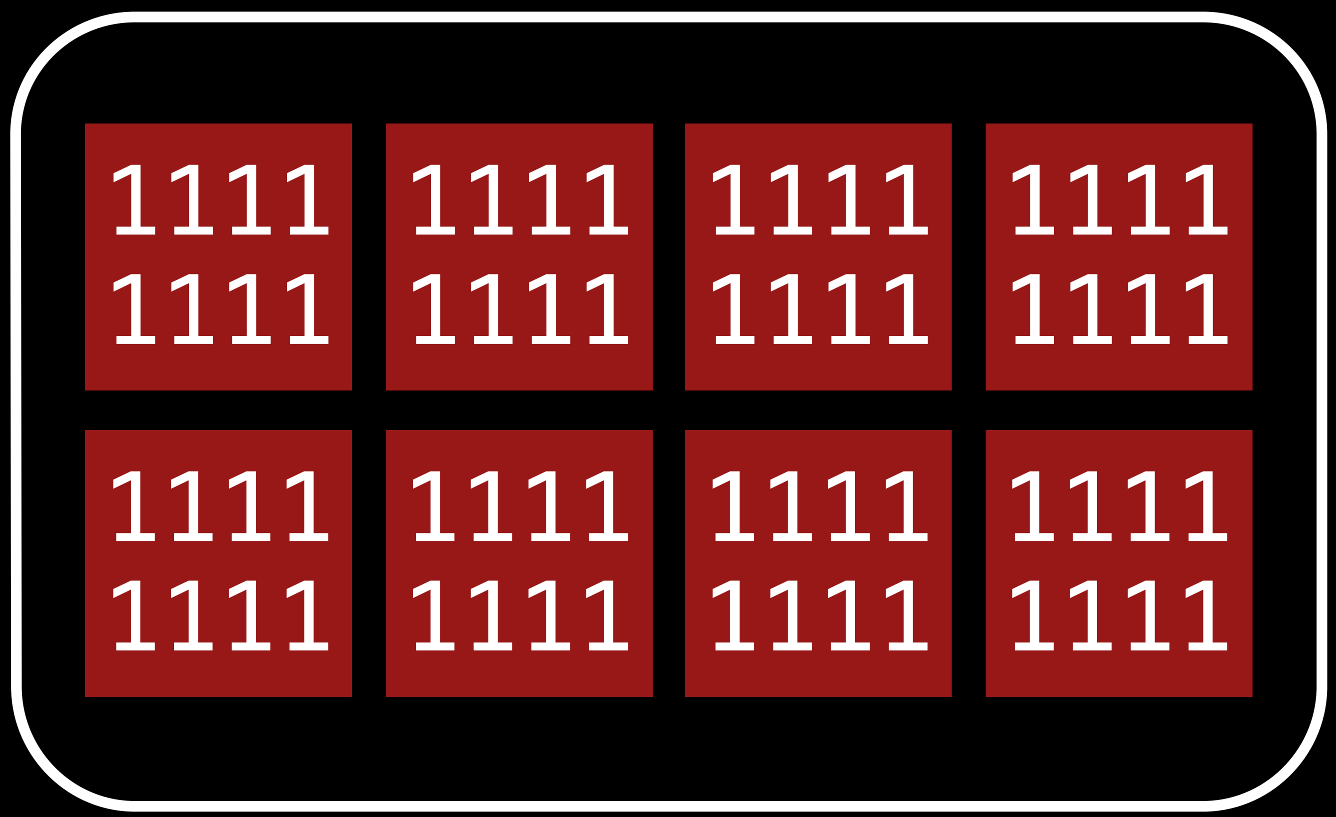
A Bank Consists of Blocks

A Bank Consists of Blocks



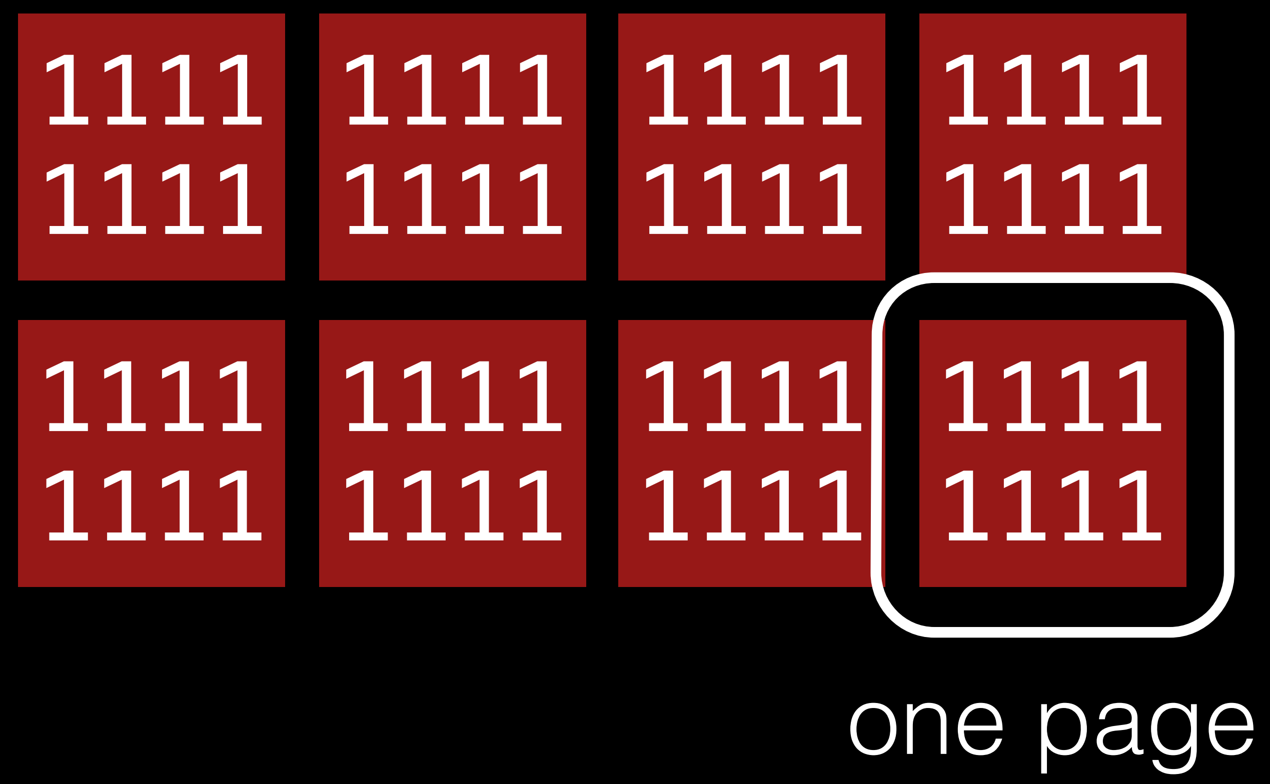
A Block Consists of Pages

A Block Consists of Pages

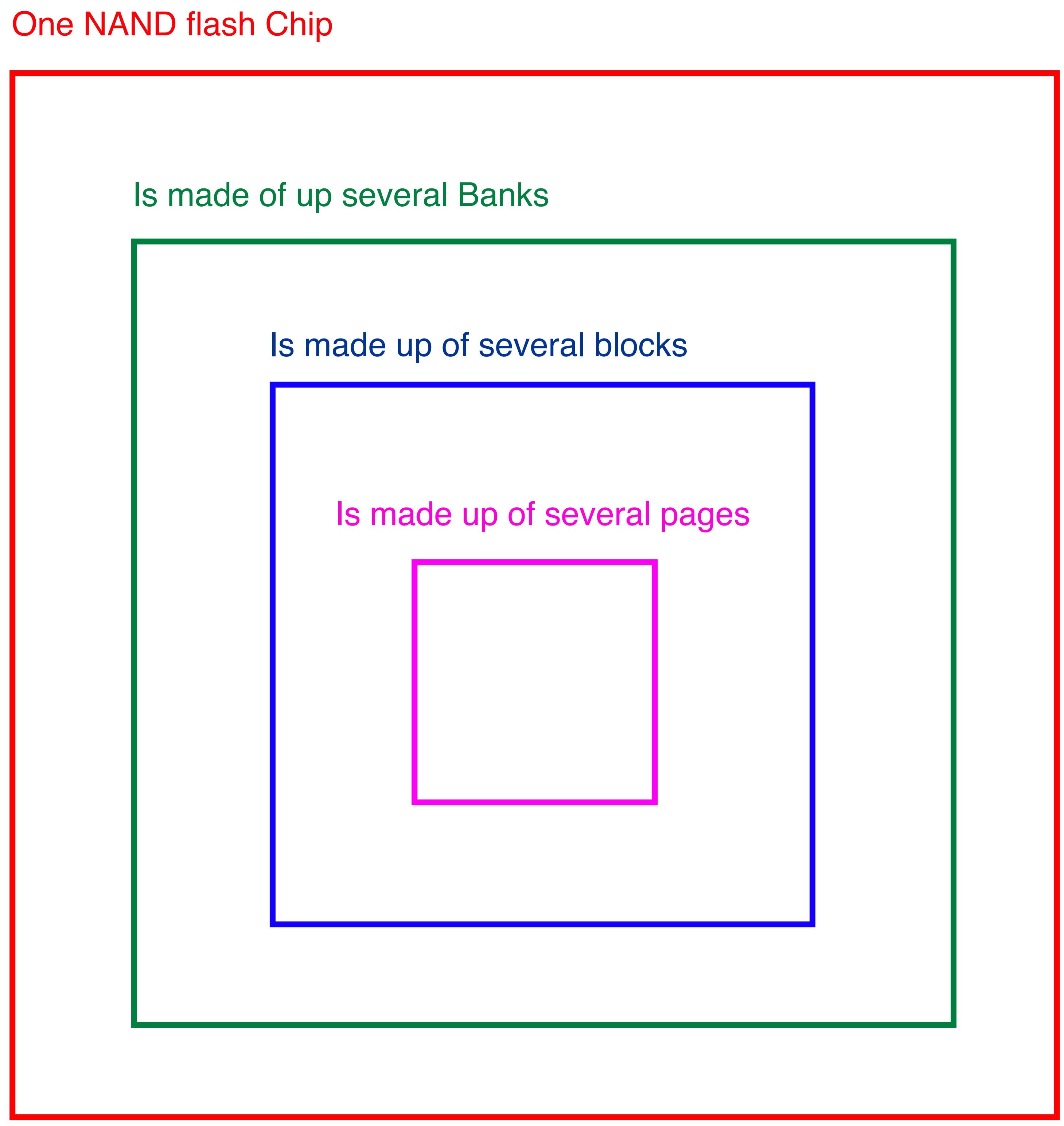


one block

Block


1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
one page

The Heirarchy of SSD components:



Block


1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111
1111

Block


program
1111
1111
1111
1111
1111
1111
1001
1111
1111
1111
1111
1111
1111
1111
1111
1111

Block

1111 1111	1111 1111	1111 1111	1001 1111
1111 1111	1111 1111	1111 1111	1111 1111

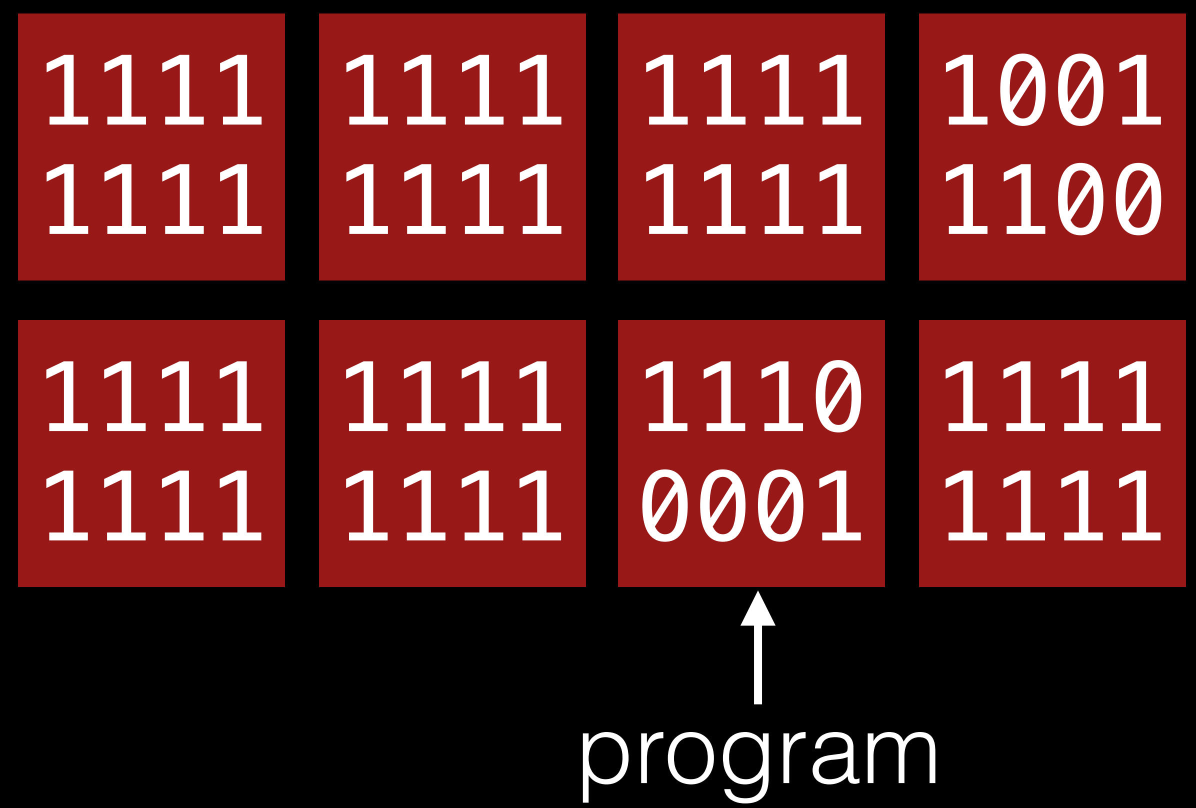
Block


program
1111
1111
1111
1111
1111
1111
1001
1100
1111
1111
1111
1111
1111
1111
1111
1111

Block

1111 1111	1111 1111	1111 1111	1001 1100
1111 1111	1111 1111	1111 1111	1111 1111

Block



1111 1111
1111 1111
1111 1111
1001 1100
1111 1111
1111 1111
1110 0001
1111 1111
program

Block

1111 1111	1111 1111	1111 1111	1001 1100
1111 1111	1111 1111	1110 0001	1111 1111

Block

1111 1111	1111 1111	1111 1111	1001 1100
1111 1111	1111 1111	1110 0001	1111 1111

erase

Block

1111 1111	1111 1111	1111 1111	1111 1111
1111 1111	1111 1111	1111 1111	1111 1111

erase

Block

1111 1111	1111 1111	1111 1111	1111 1111
1111 1111	1111 1111	1111 1111	1111 1111

APIs

	disk	flash
read		
write		

APIs

	disk	flash
read	read sector	read page
write		

APIs

	disk	flash
read	read sector	read page
write	write sector	program page (0's) erase block (1's)

Flash Chip Hierarchy

Plane: 1024 to 4096 blocks
- planes accessed in parallel

Block: 64 to 256 pages
- unit of erase

Page: 2 to 8 KB
- unit of read and program

Flash **Chip** Hierarchy

Plane: 1024 to 4096 blocks
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- unit of read and program

Channel: The number of **chips** that the controller can talk to sumultaneously
- Low end SSDs: 2-4 channels
- High end SSDs: 8+ channels

Disk vs. Flash Performance

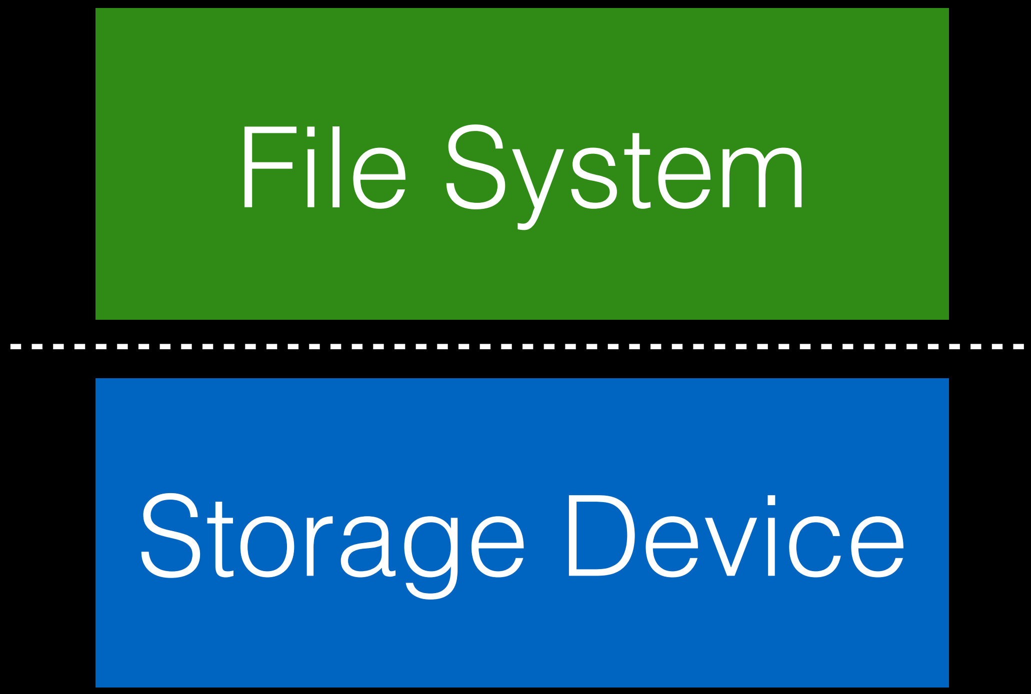
Throughput:
- disk: ~130 MB/s (sequential)
- flash: ~200 MB/s - 550 MB/s

Disk vs. Flash Performance

Throughput:
- disk: ~130 MB/s (sequential)
- flash: ~200 MB/s **- 550 MB/s**

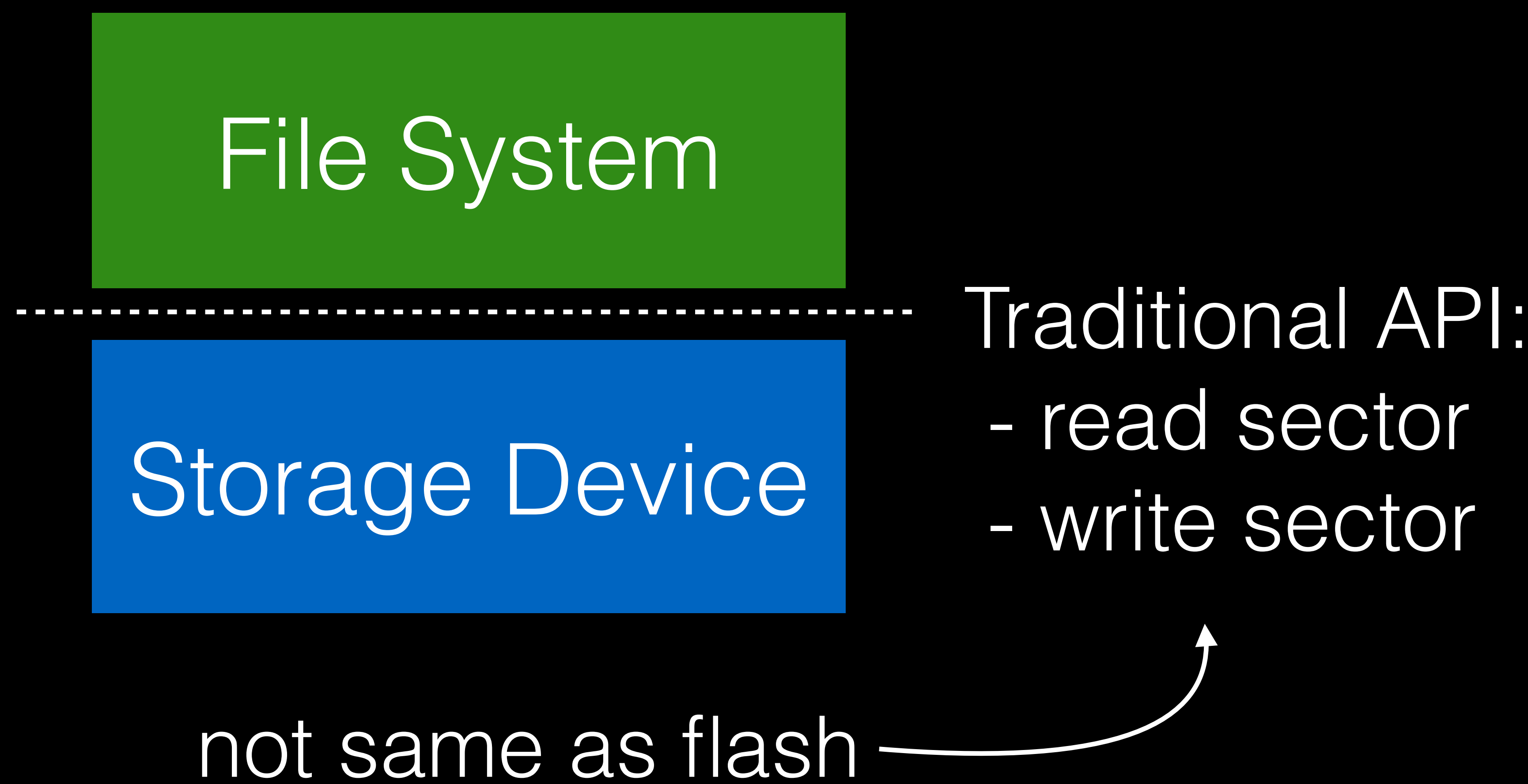
Latency
- disk: ~10 ms (one op)
- flash
  - read: 10-50 us
  - program: 200-500 us
  - erase: 2 ms

Traditional File Systems



Traditional API:
- read sector
- write sector

Traditional File Systems



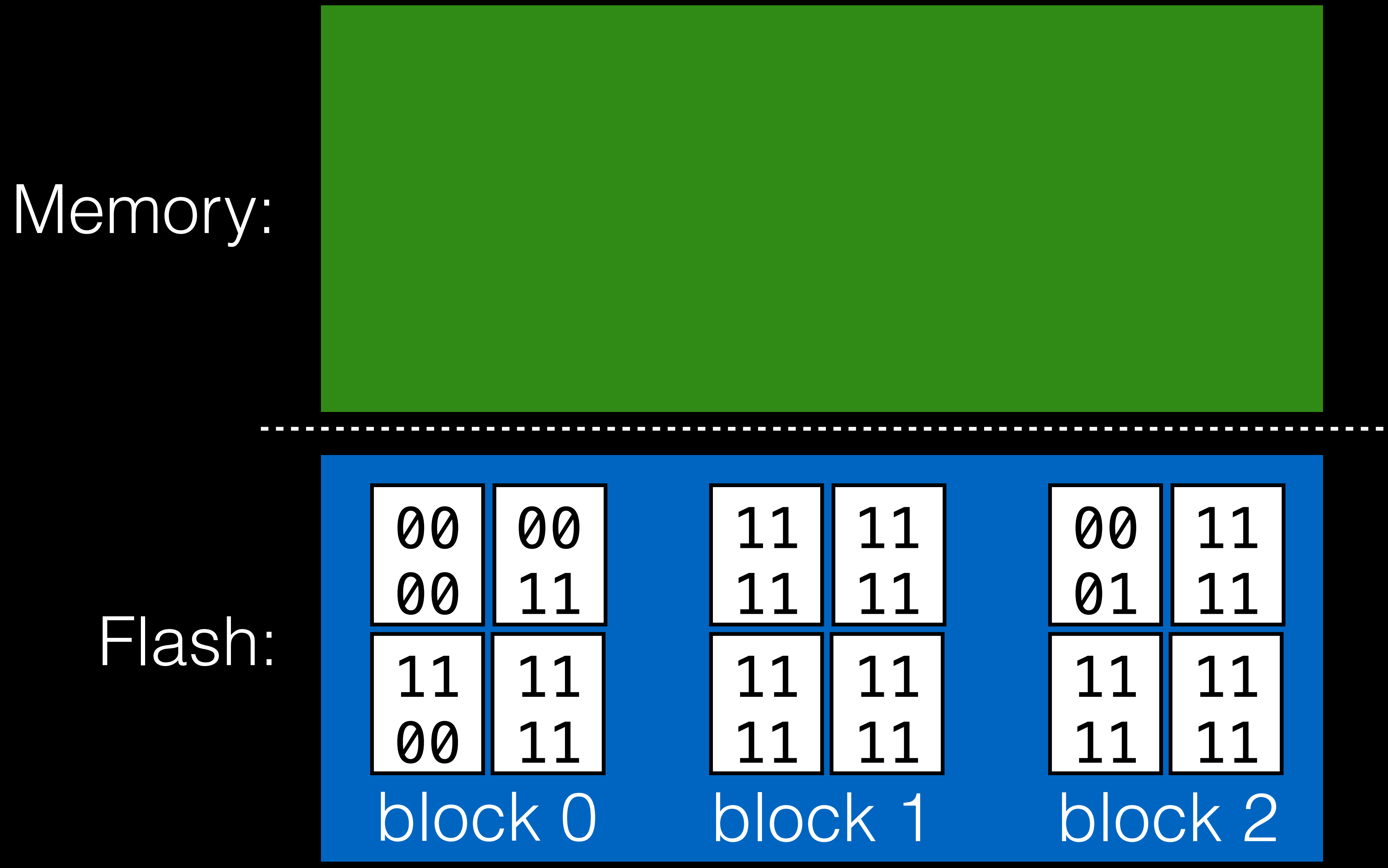
Options

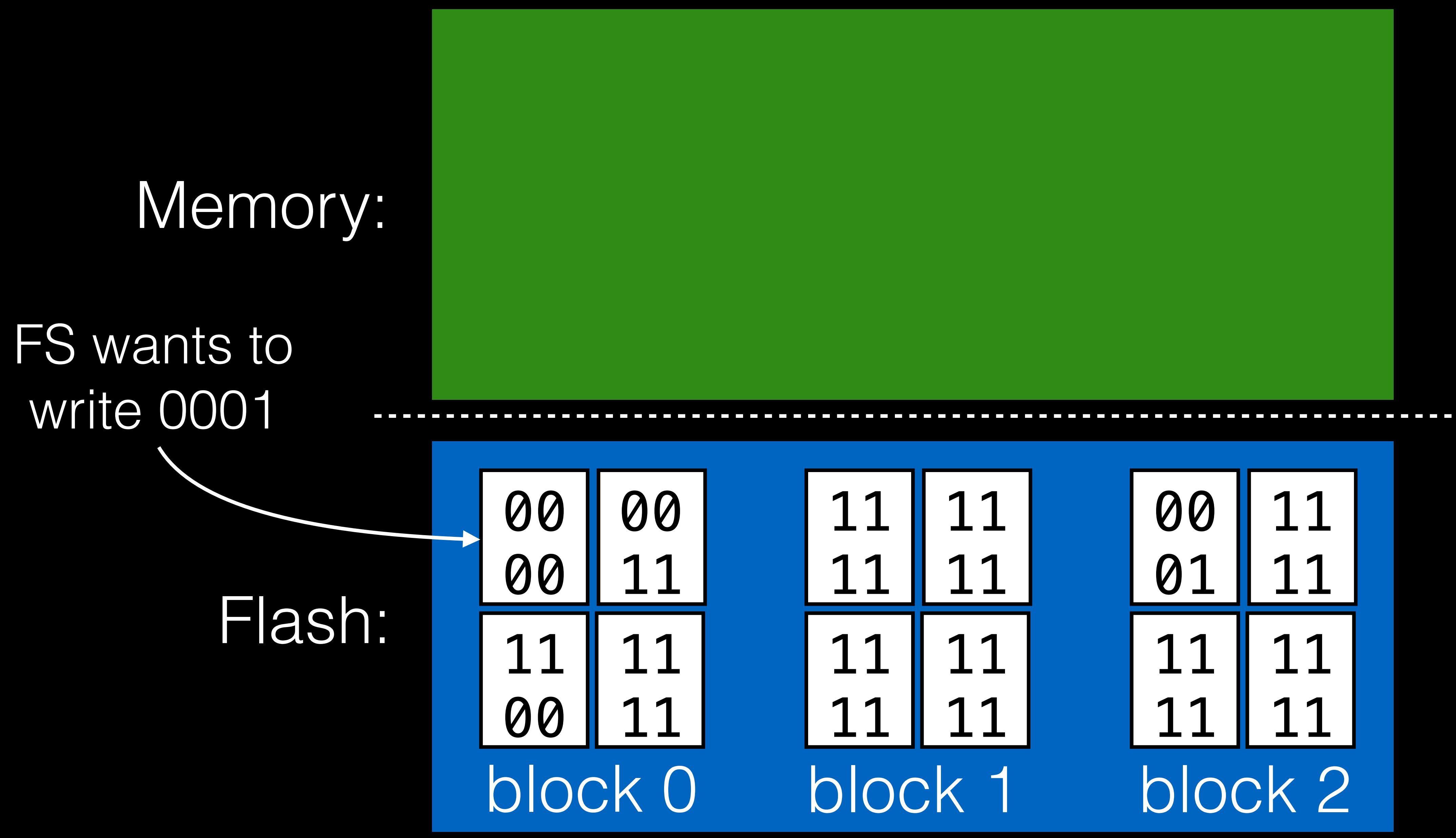
1. Build/use new file systems for flash
 - Example: JFFS, YAFFS
 - Problem: this takes a lot of work!

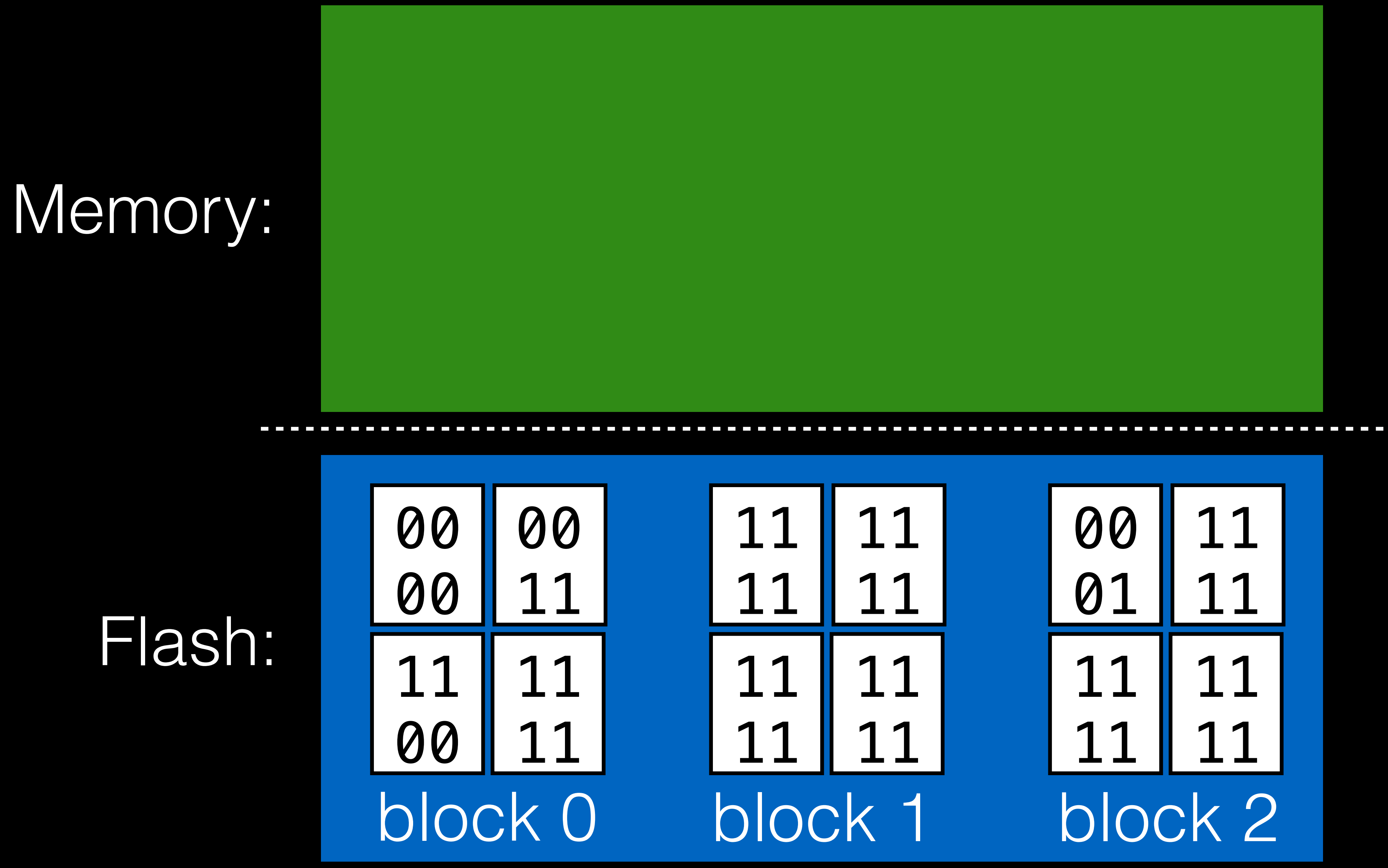
2. Translate traditional API onto flash API.
 - then we can use FFS, LFS, etc. without any additional work!

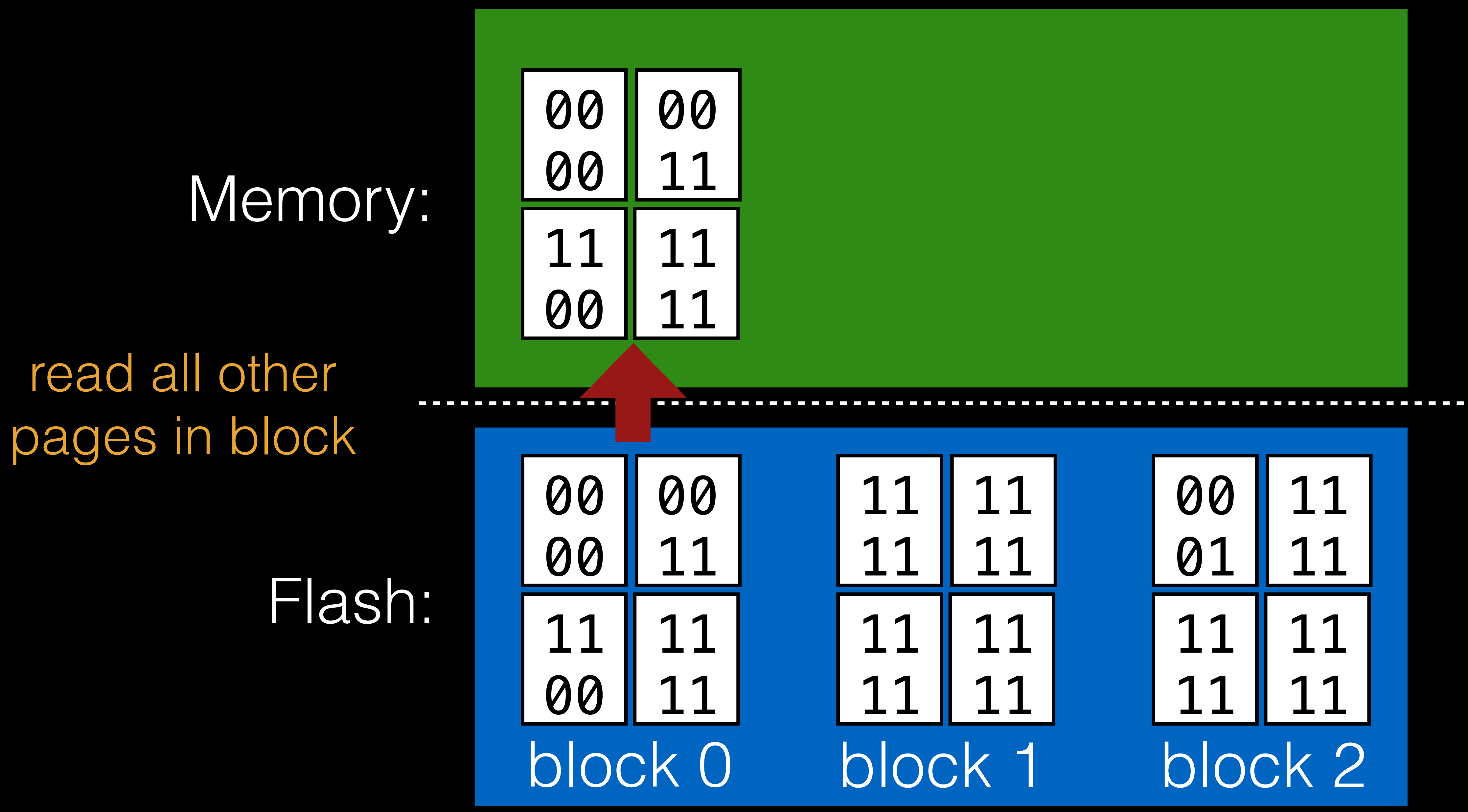
Traditional API -> Flash: attempt 1

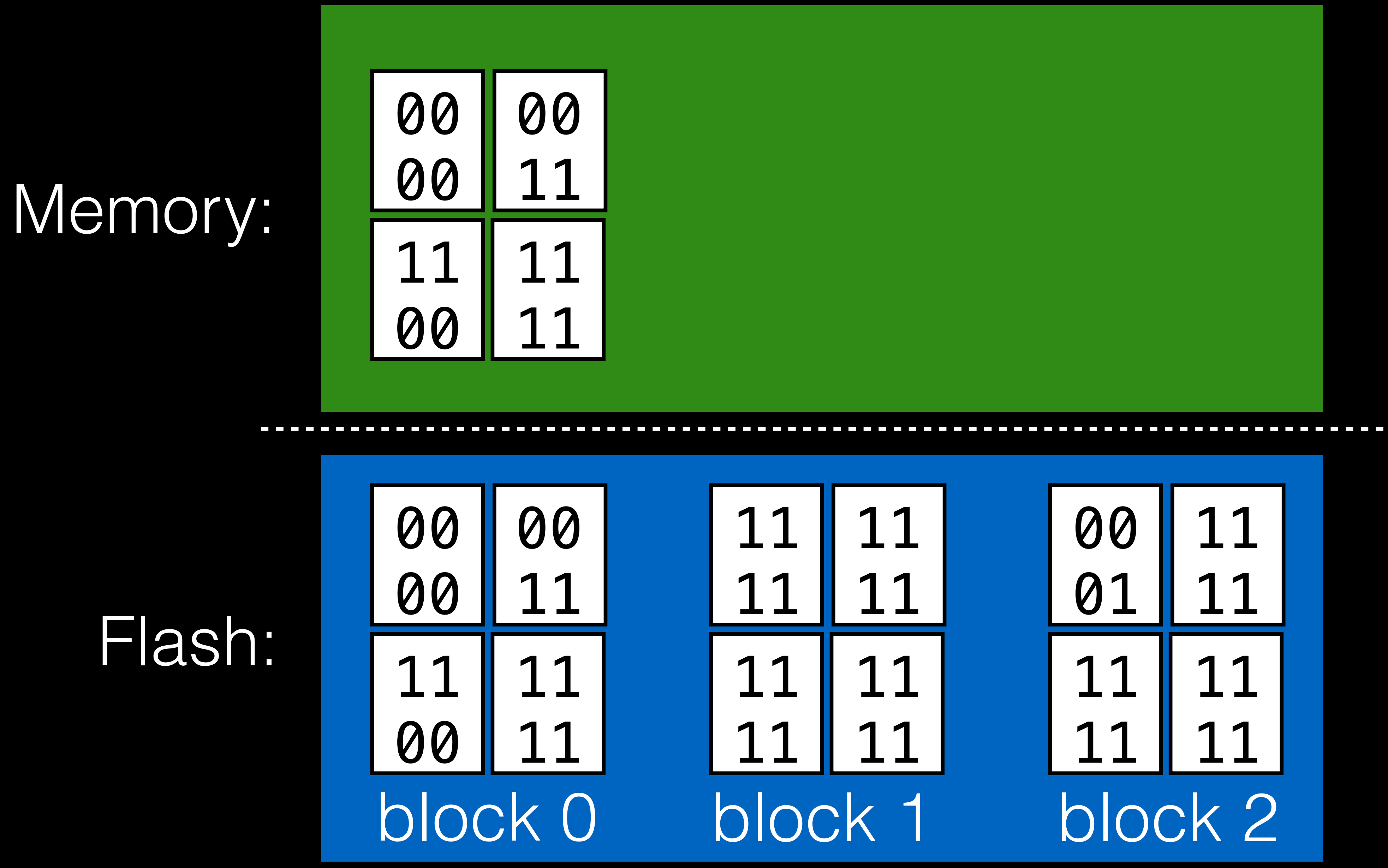
```
read(addr):
    return flash_read(addr)

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


Memory:
Flash:
00
00
00
11
11
00
11
11
11
11
11
11
11
11
11
11
00
01
11
11
11
11
11
11
block 0
block 1
block 2

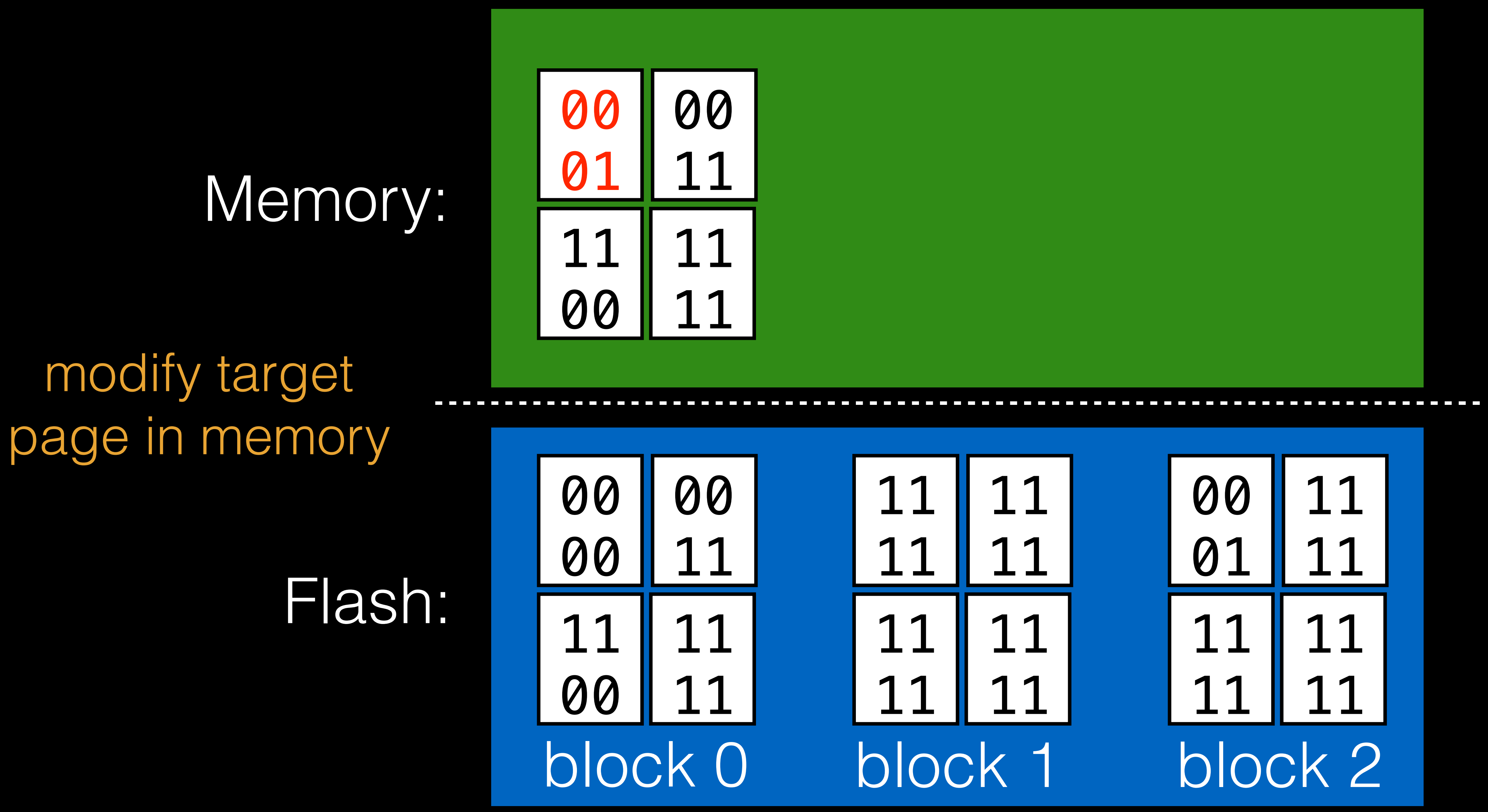

Memory:
FS wants to
write 0001
Flash:
00
00
00
11
11
00
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2


Memory:
Flash:
00
00
00
11
11
00
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2

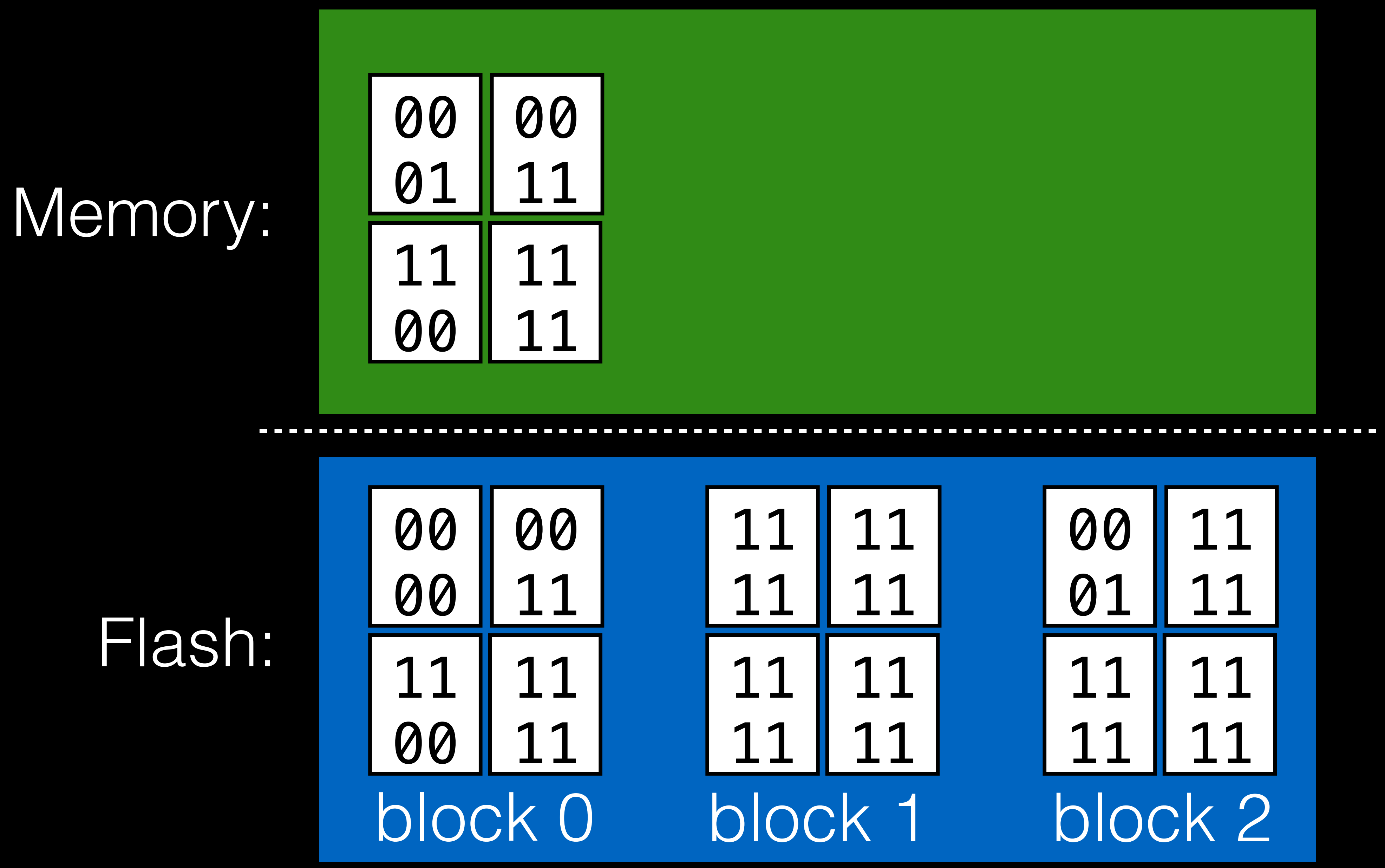

Memory:
00
00
00
11
11
00
11
11
read all other
pages in block
Flash:
00
00
00
11
11
00
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2

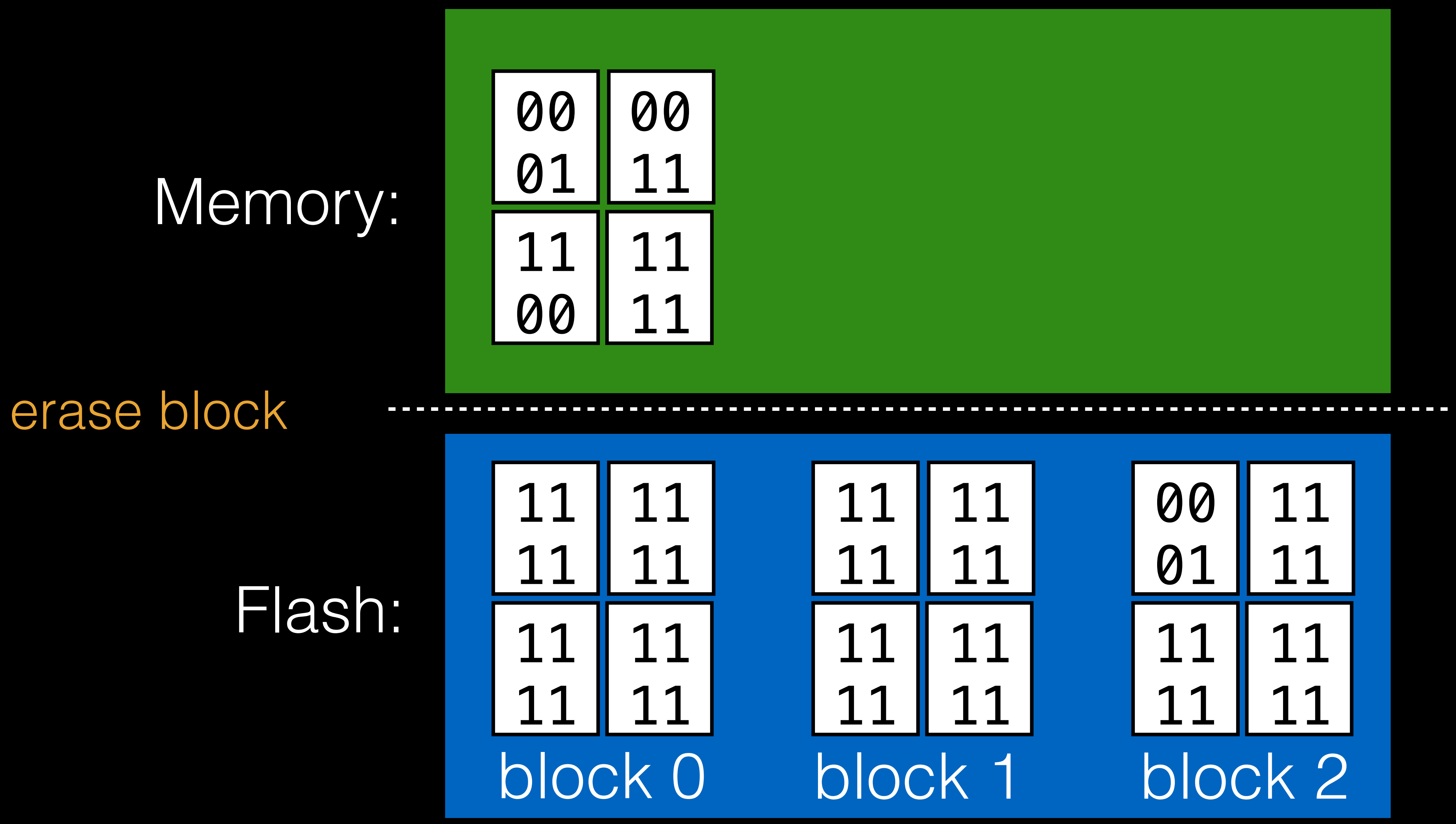


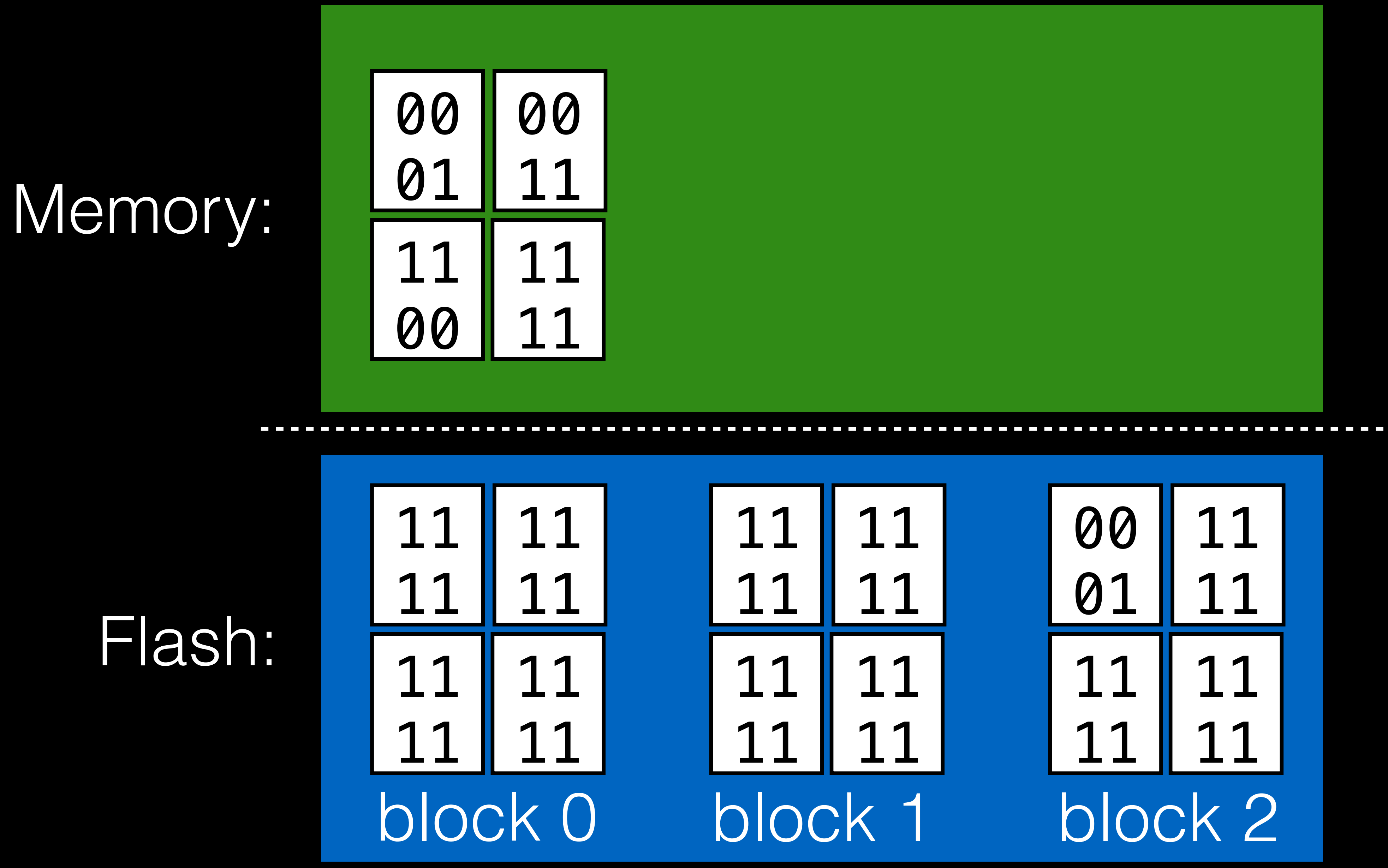
Memory:
00
00
00
11
11
00
11
11
Flash:
00
00
00
11
11
00
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2

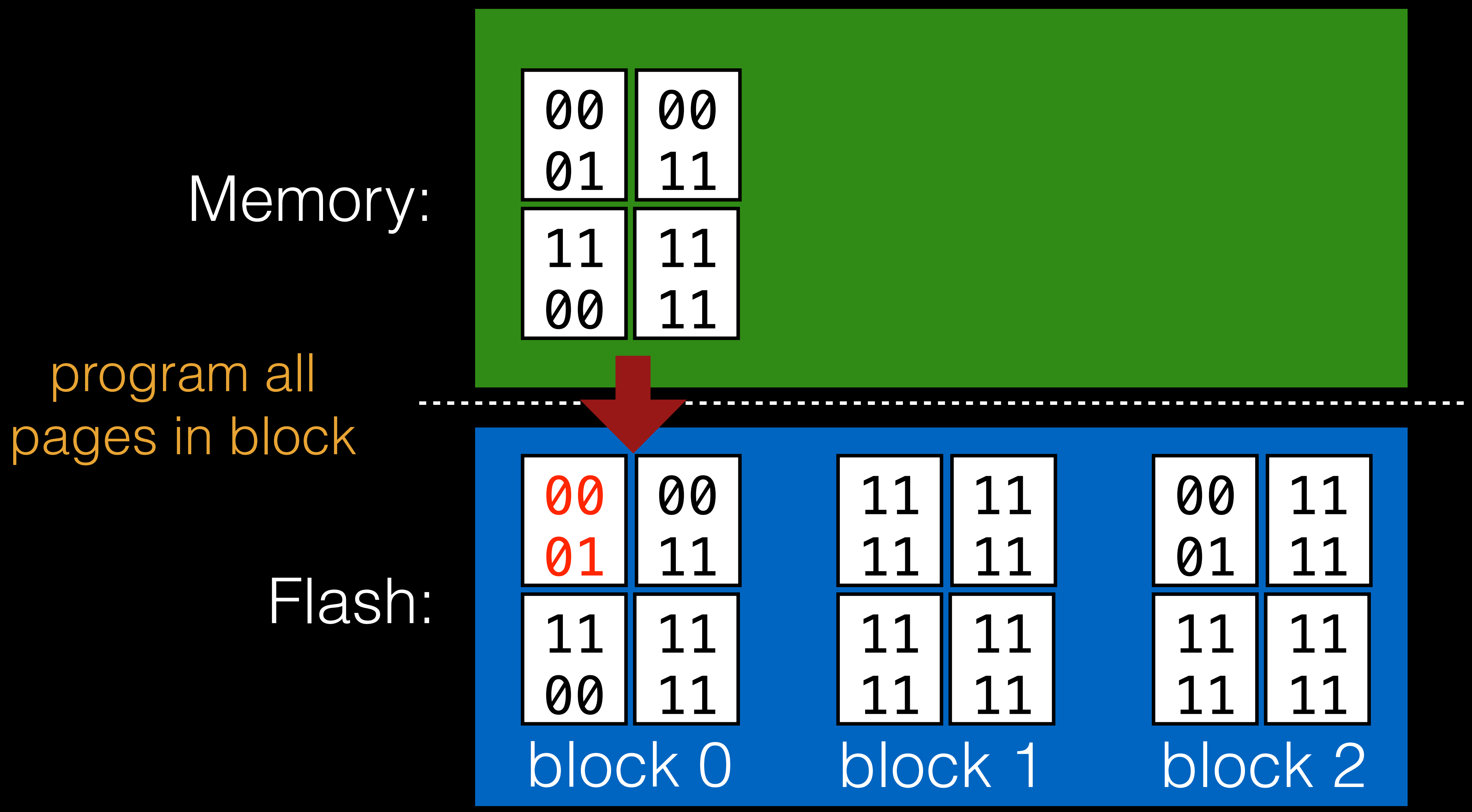


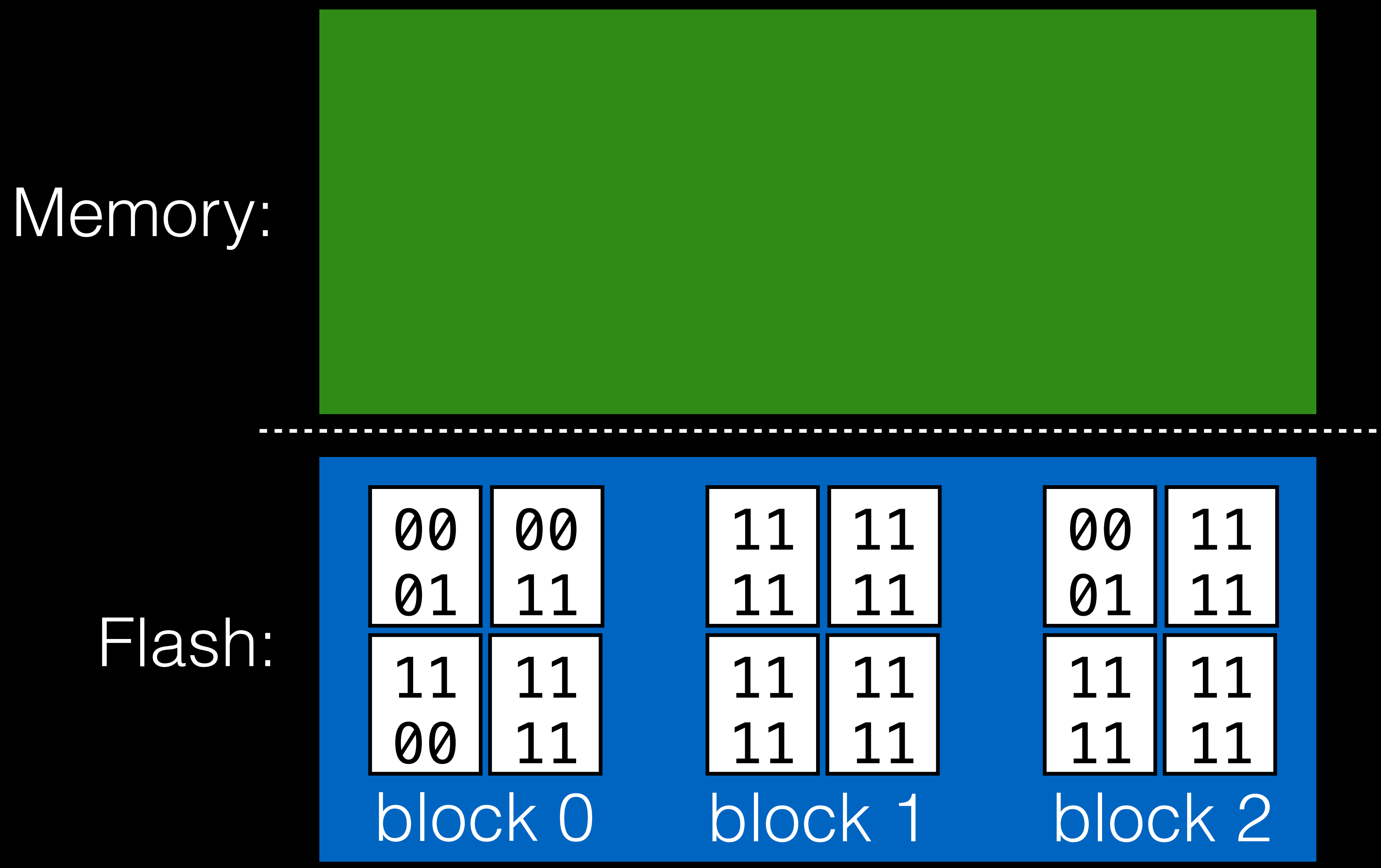
Memory:
00
01
00
11
11
00
11
11
modify target
page in memory
Flash:
00
00
00
11
11
00
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2


Memory:
00
01
00
11
11
00
11
11
Flash:
00
00
00
11
11
00
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2


Memory:
00
01
00
11
11
00
11
11
erase block
Flash:
11
11
11
11
11
11
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2


Memory:
00
01
00
11
11
00
11
11
Flash:
11
11
11
11
11
11
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2


Memory:
00
01
00
11
11
00
11
11
program all
pages in block
Flash:
00
01
00
11
11
00
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2


Memory:
Flash:
00
01
00
11
11
00
11
11
block 0
11
11
11
11
11
11
11
11
block 1
00
01
11
11
11
11
11
11
block 2

Write Amplification

Problem: Random writes are extremely expensive!

Writing one 2KB page may cause:
- `read`, `erase`, and `program` of 256KB block.

Write Amplification

Problem: Random writes are extremely expensive!

Writing one 2KB page may cause:

- `read`, `erase`, and `program` of 256KB block.

Would FFS or LFS be better with flash?

File Systems over Flash

Copy-On-Write FS *may* prevent some expensive random writes.

File Systems over Flash

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What about wear leveling?

File Systems over Flash

Copy-On-Write FS *may* prevent some expensive random writes.

What about wear leveling? LFS won't do this.

File Systems over Flash

Copy-On-Write FS *may* prevent some expensive random writes.

What about wear leveling? LFS won't do this.

What if we want to use some other FS?

(Perhaps some other FS has features or APIs our applications rely on, so we must use it)

Better Solution

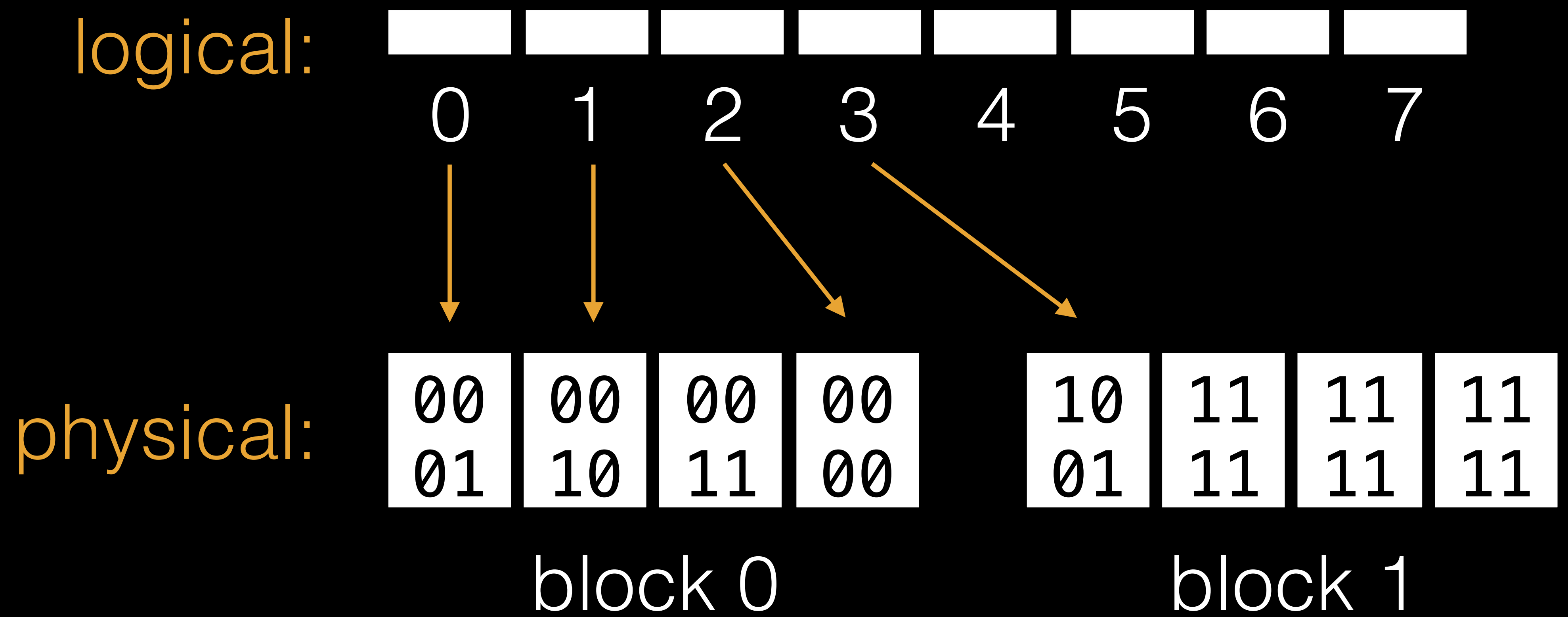
Add copy-on-write translation layer between FS and flash. Avoids RMW (read-modify-write) cycle.

Translate logical device addrs to physical addrs.

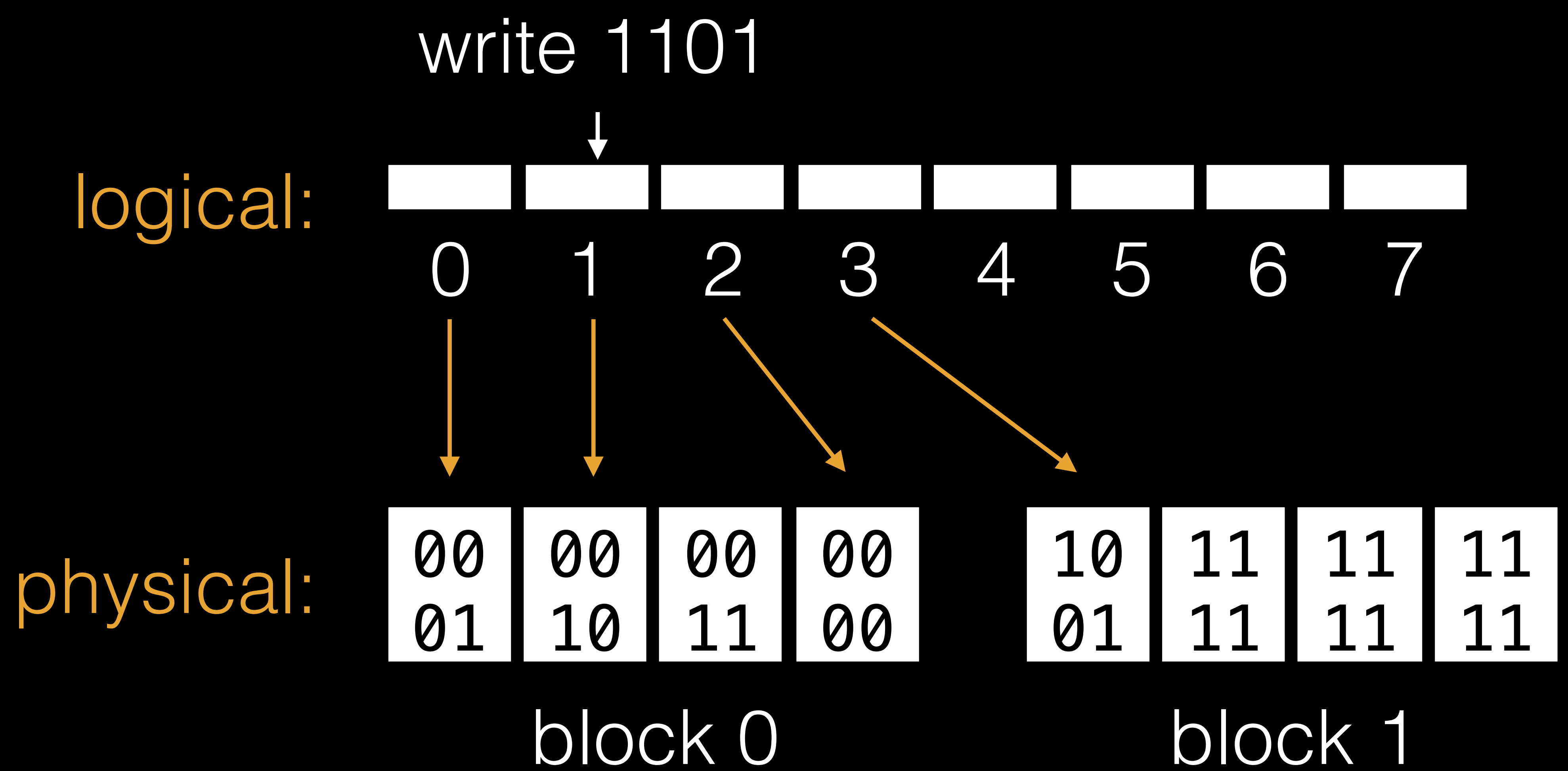
FTL: Flash Translation Layer.

Question: How should translations be managed?

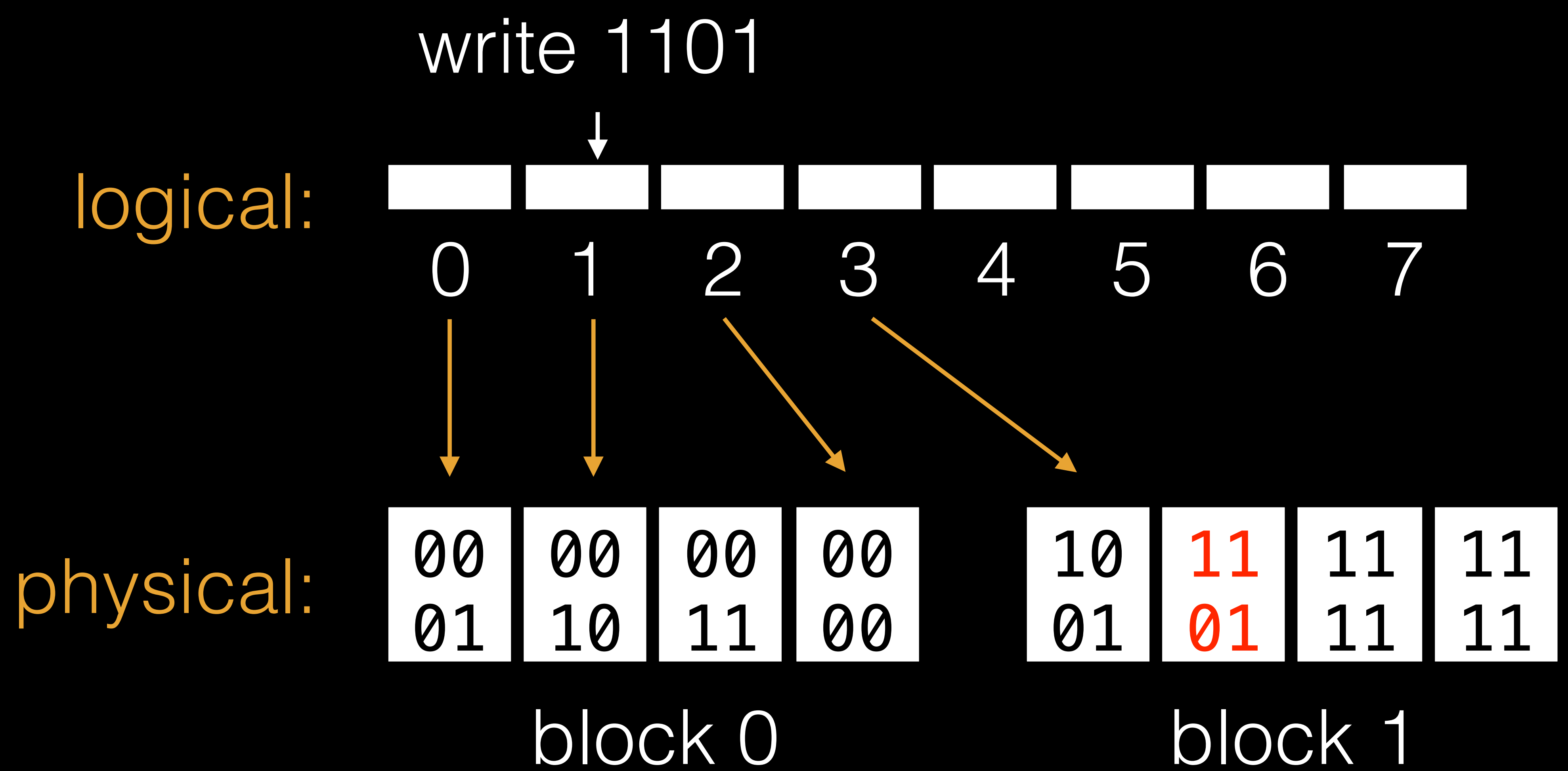
Flash Translation Layer



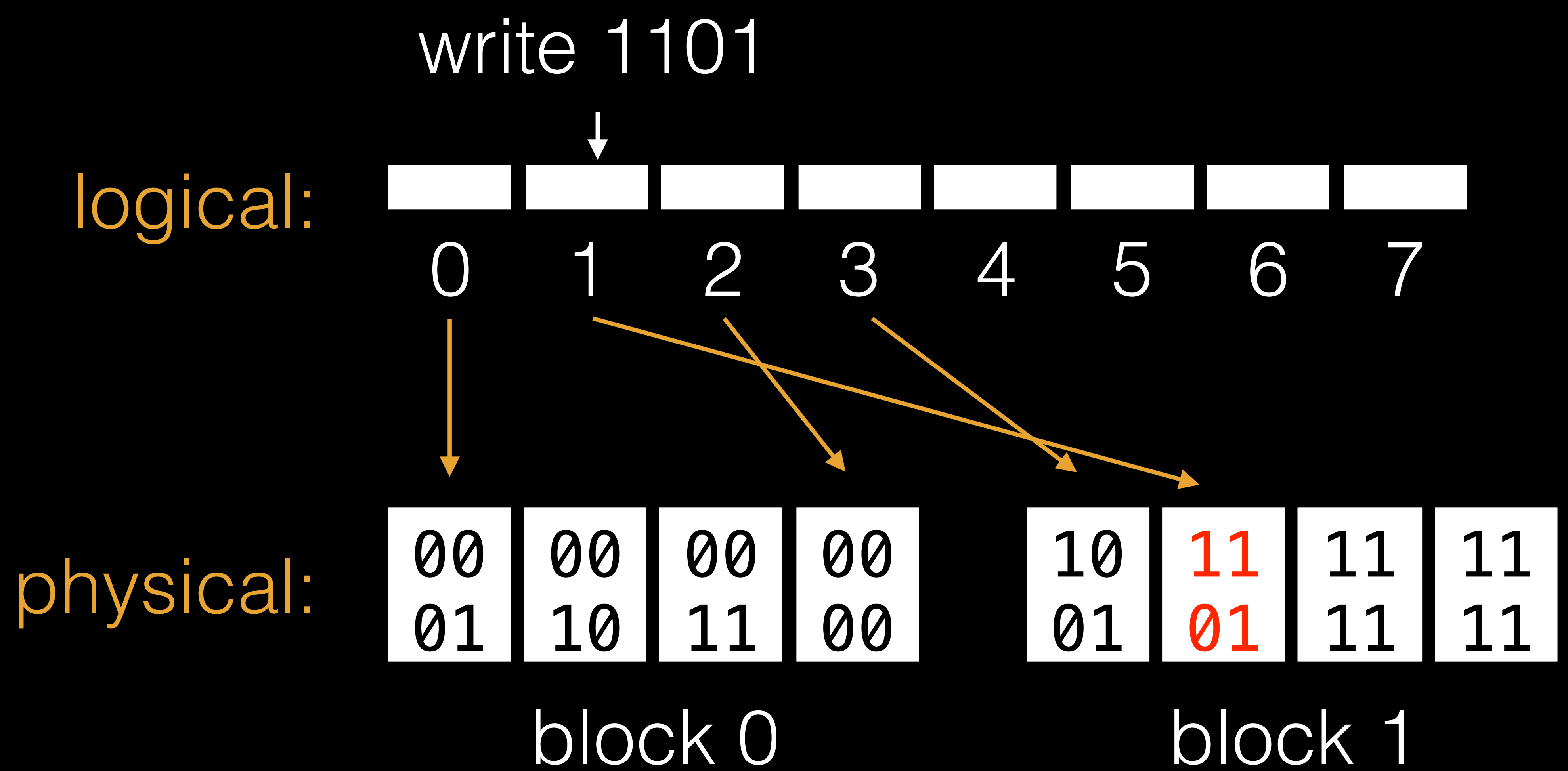
Flash Translation Layer



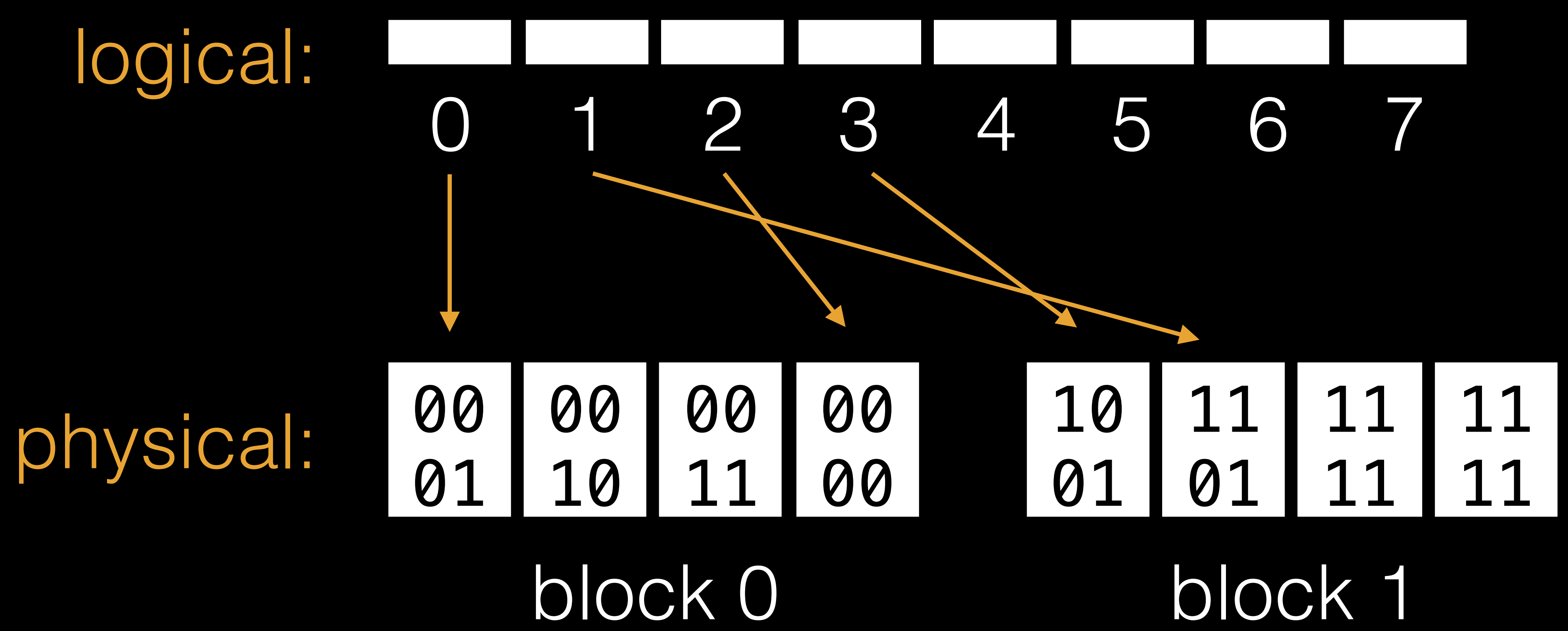
Flash Translation Layer



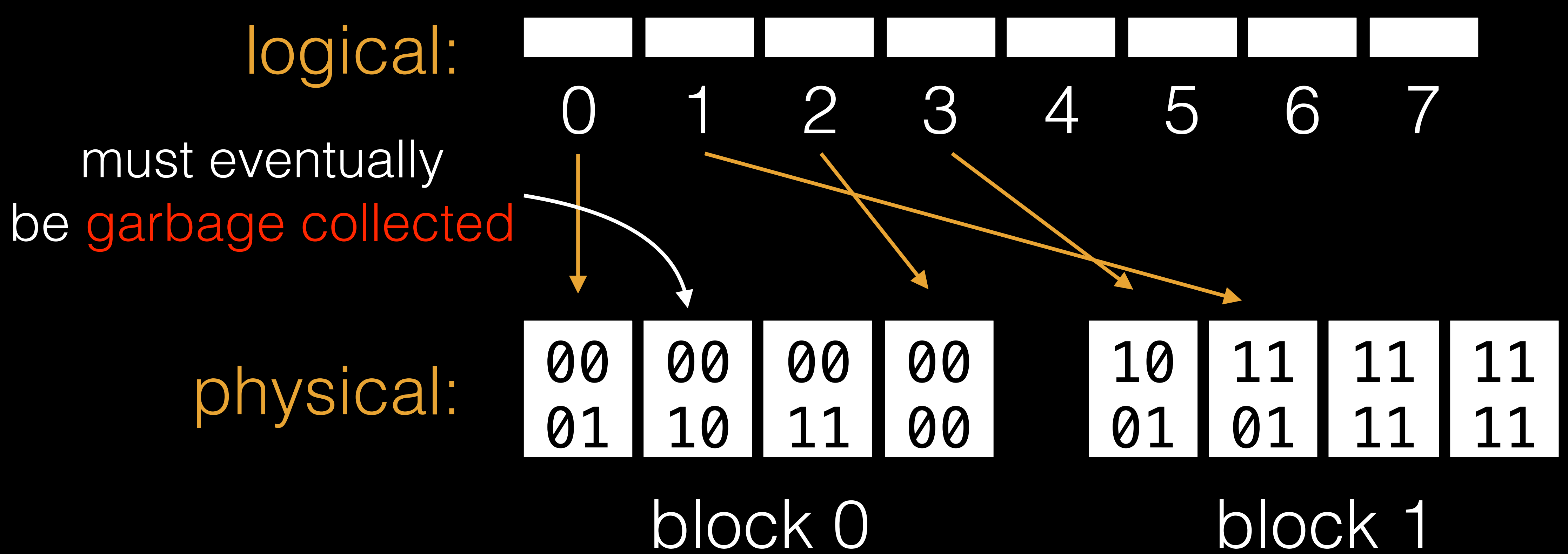
Flash Translation Layer



Flash Translation Layer



Flash Translation Layer



FTL

Could be implemented as device driver (OS) or in firmware (code running on SSD).

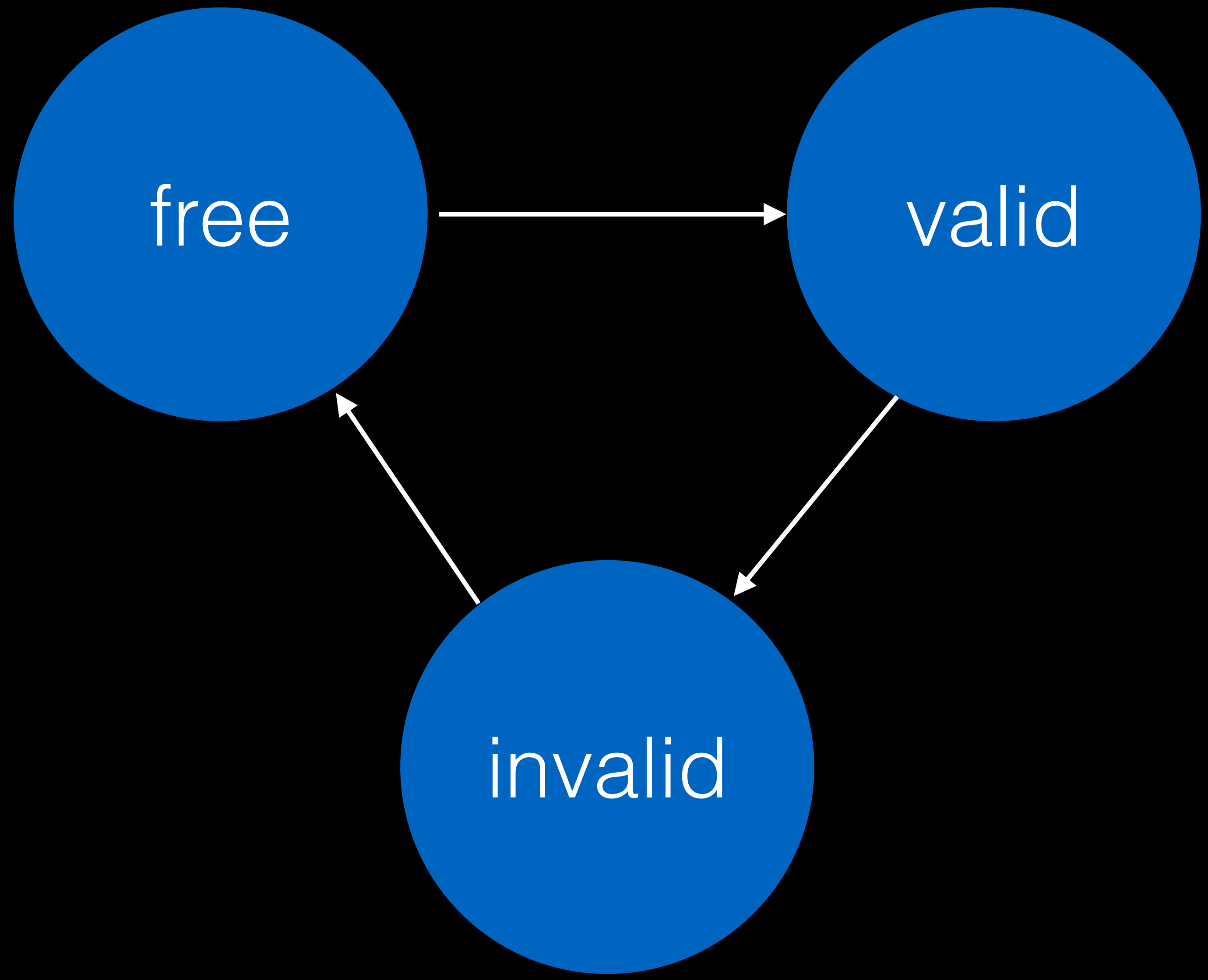
- usually done in firmware

Where to store LBA->PBA mappings? SRAM.

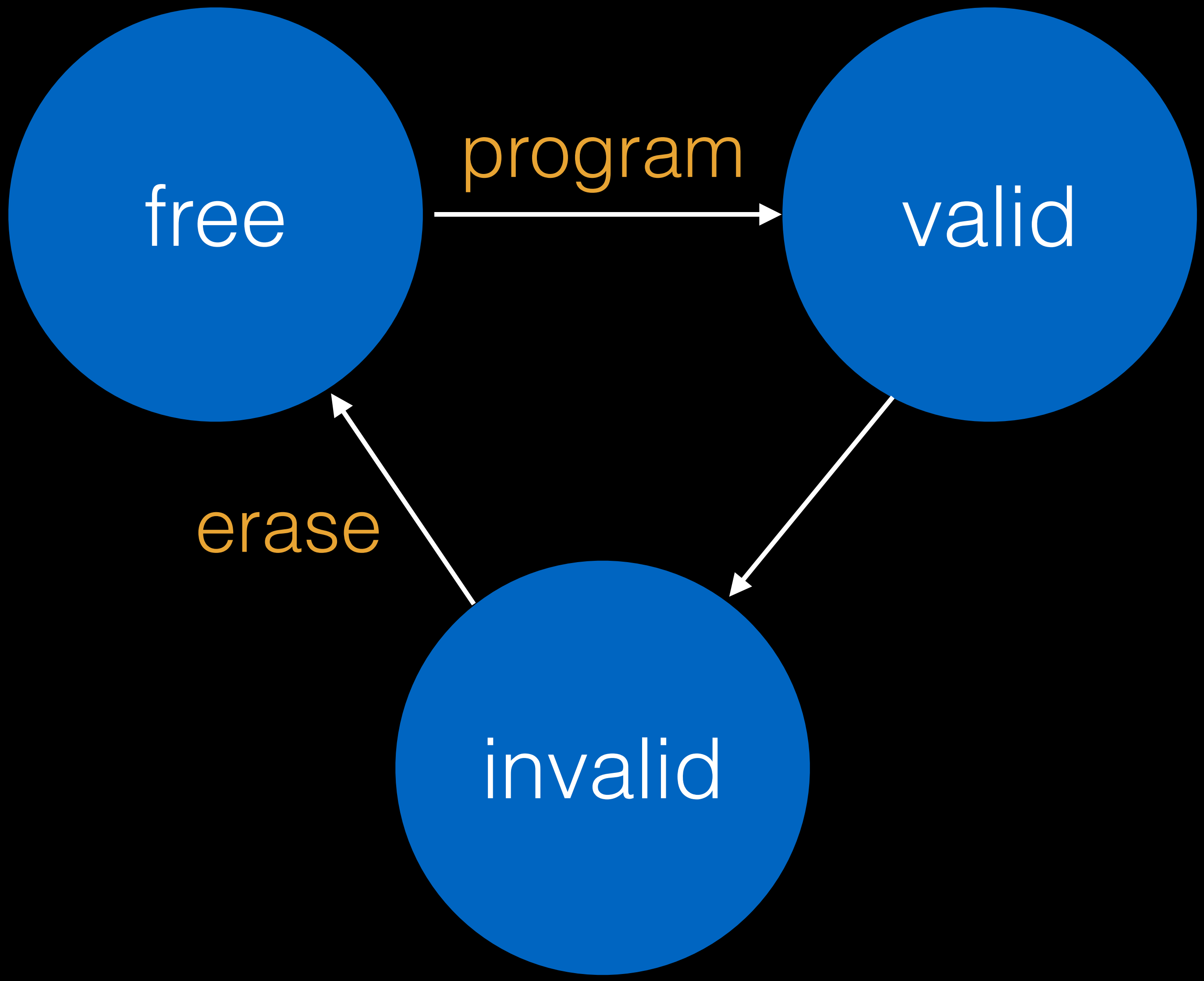
Physical pages can be in three states:

- valid, invalid, free

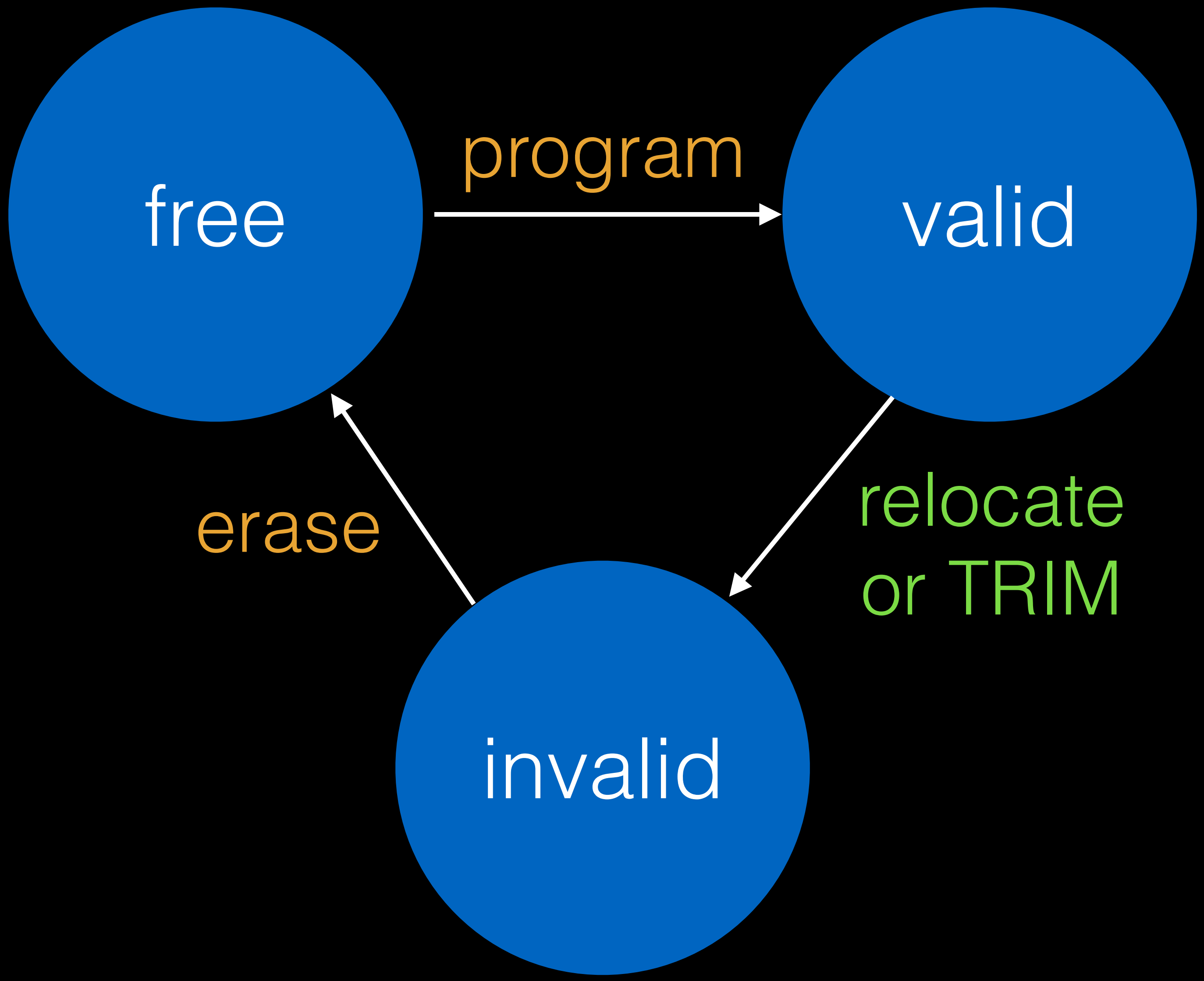
States



States

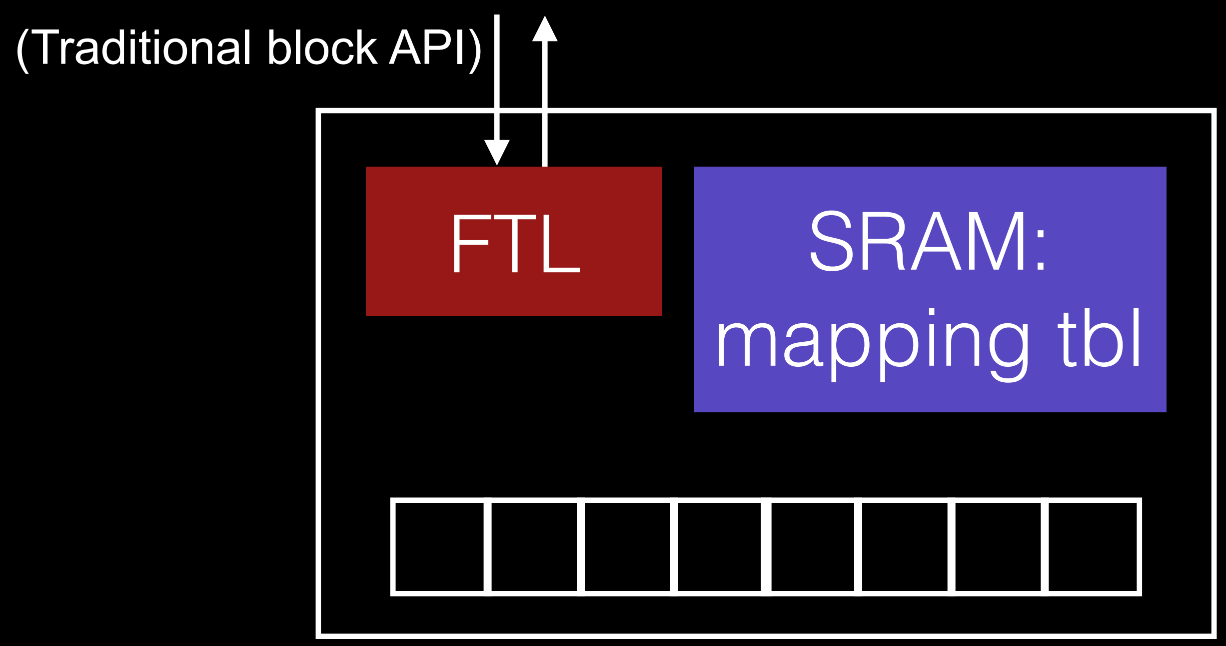


States



SSD Architecture

SSD: looks like a traditional disk



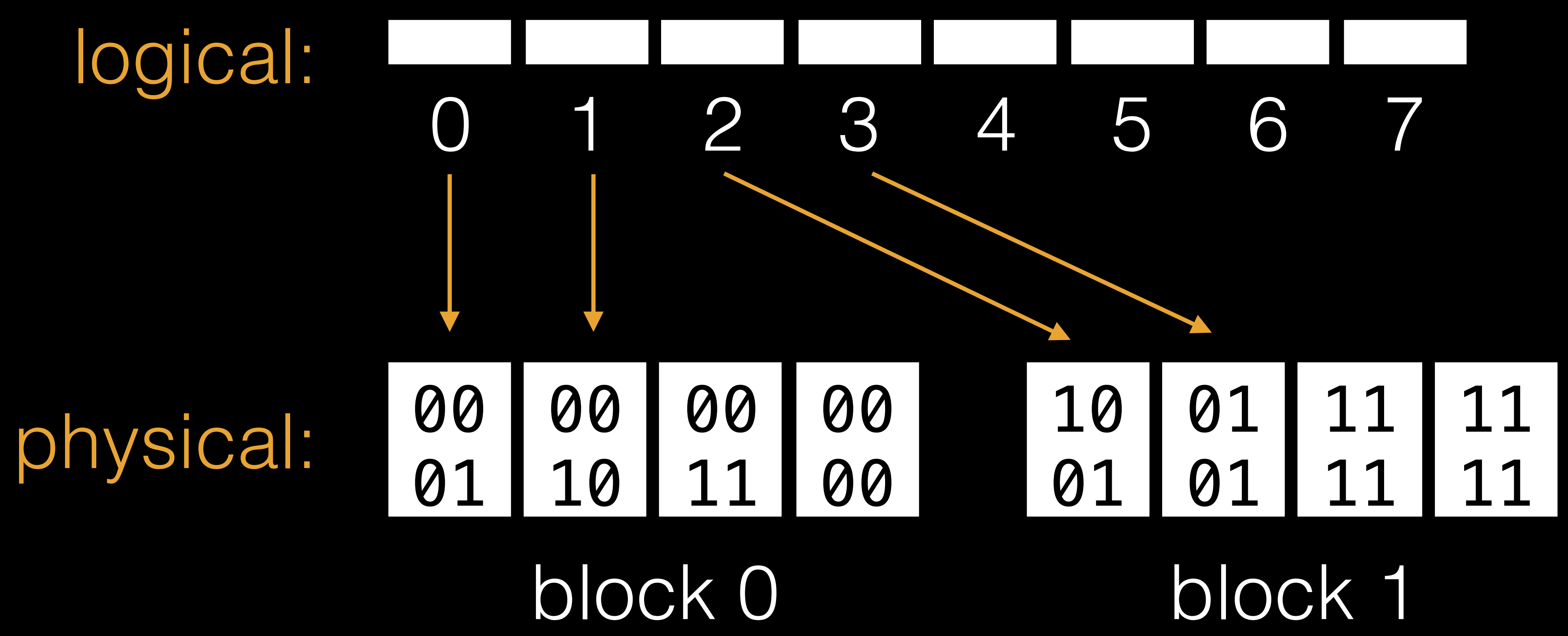
Problem: Big Mapping Table

Assume 200GB device, 2KB pages, 4-byte entries.

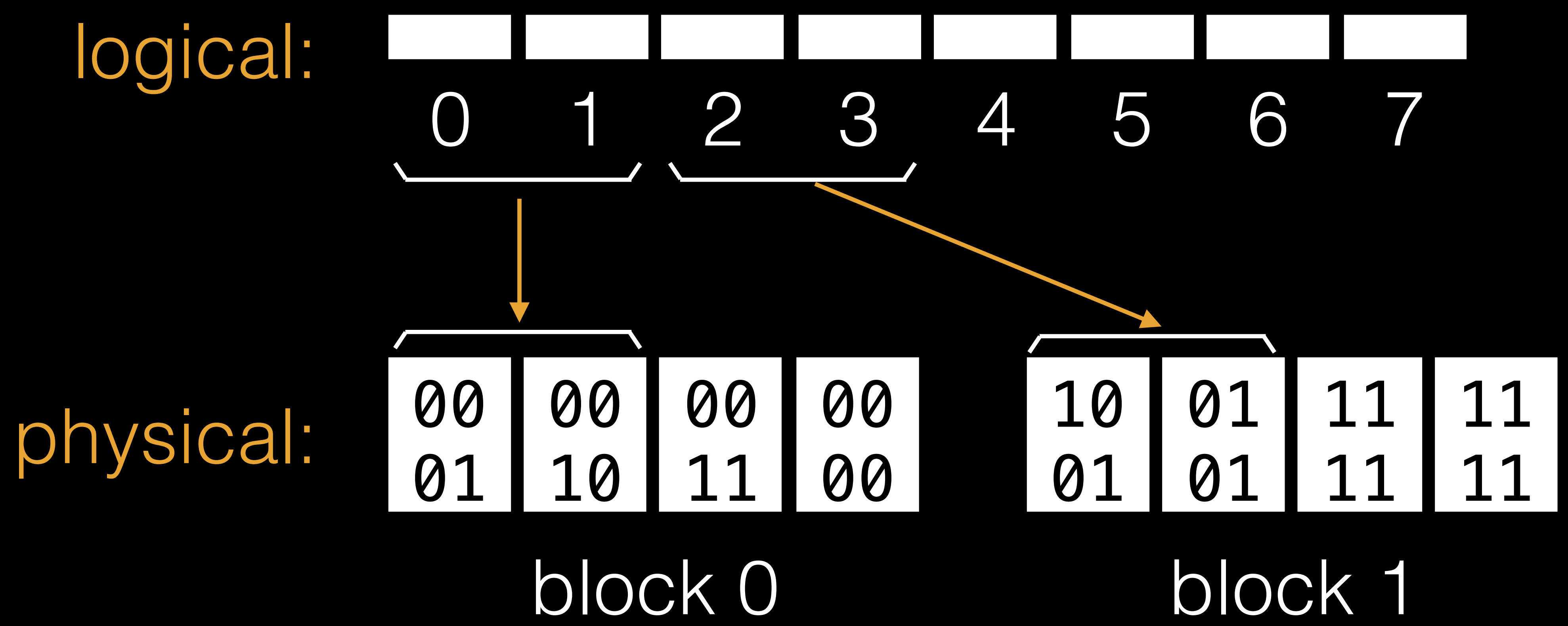
SRAM needed: (200GB / 2KB) * 4 bytes = 400 MB.

That table would be too big, SRAM is expensive!

Page Translations



2-Page Translations

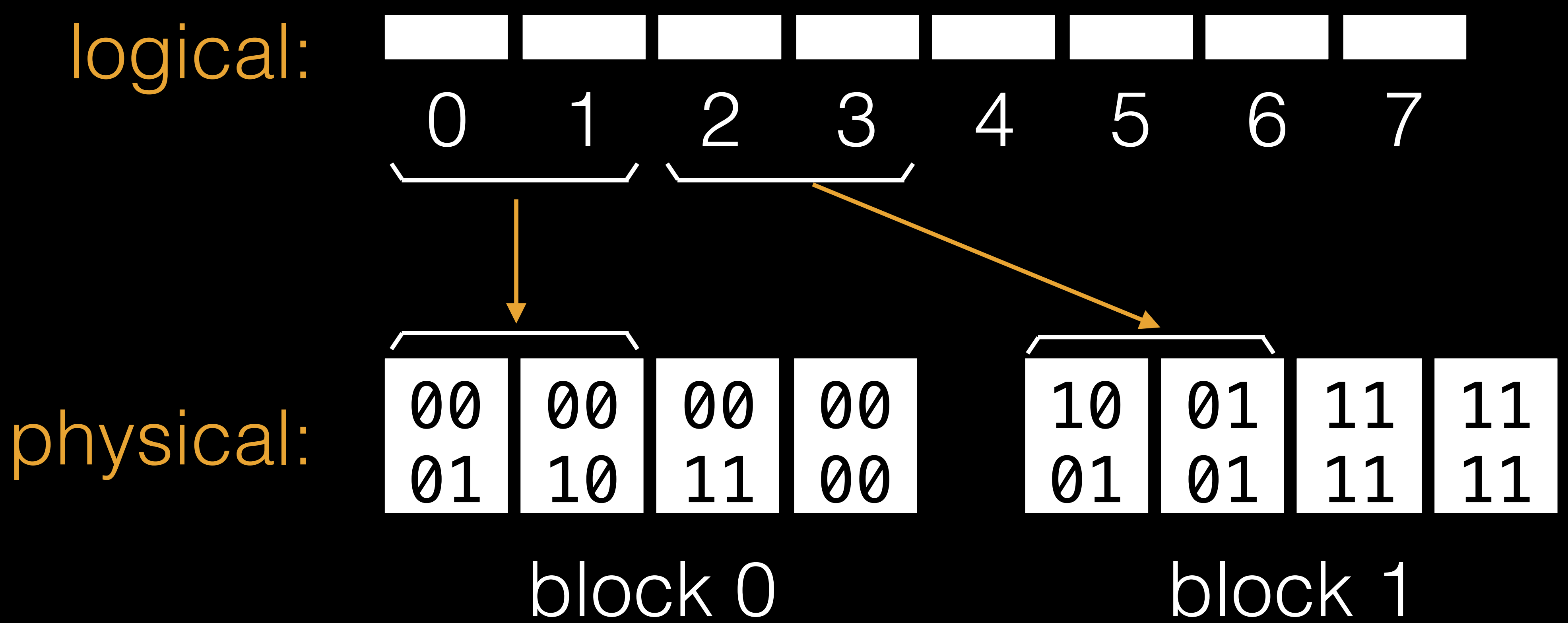


Larger Mappings

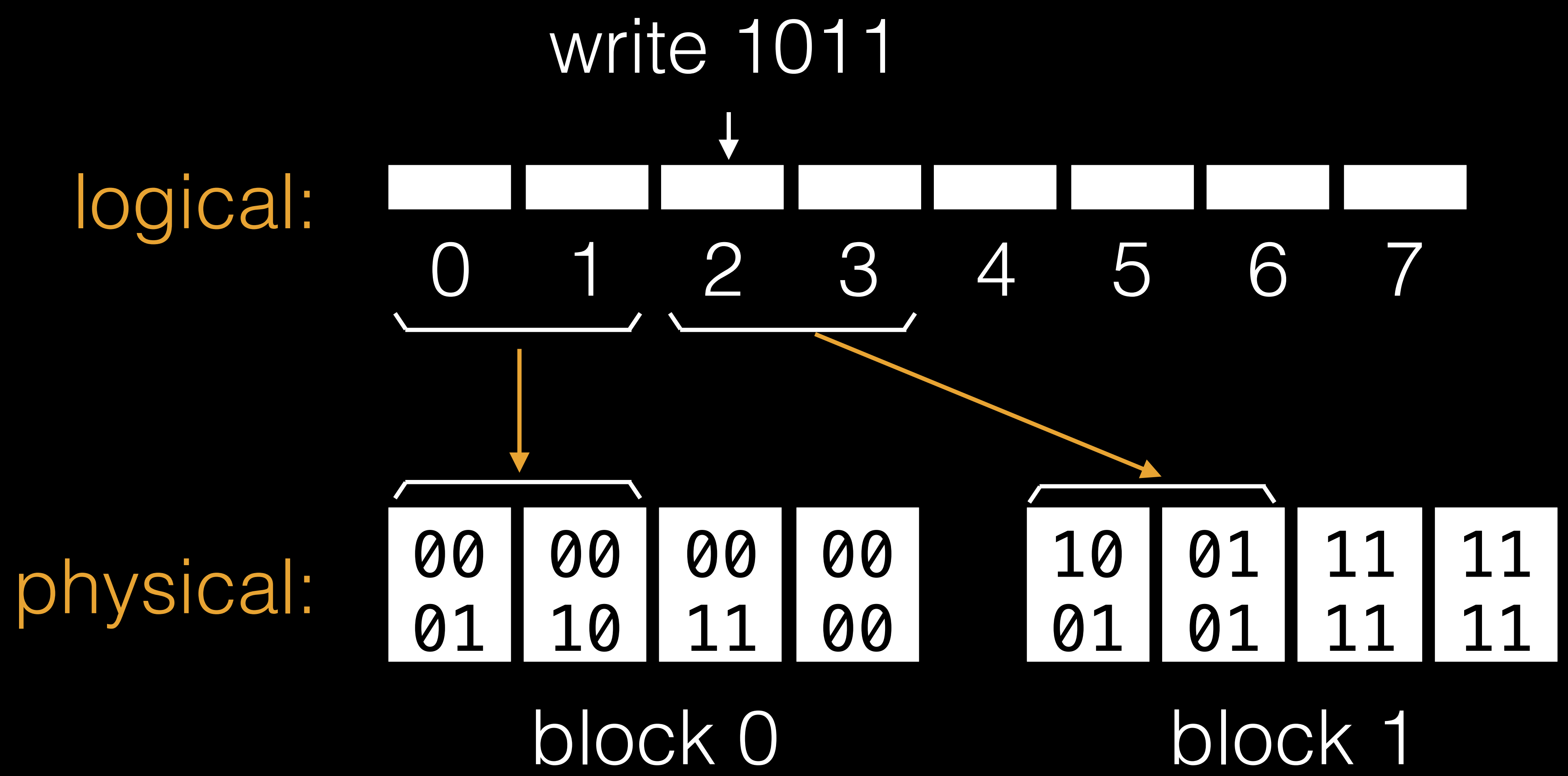
Advantage: larger mappings decrease table size.

Disadvantage?

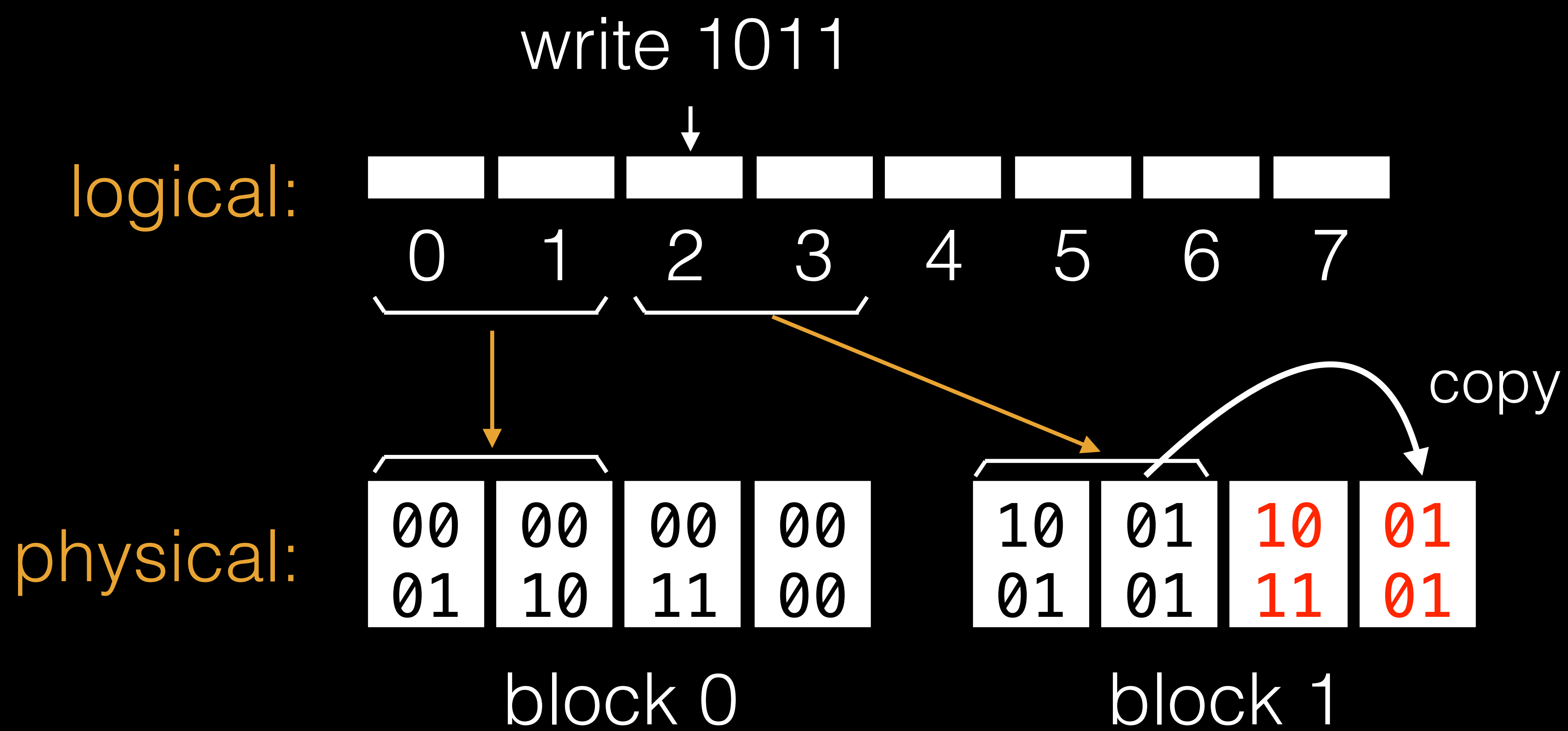
2-Page Translations



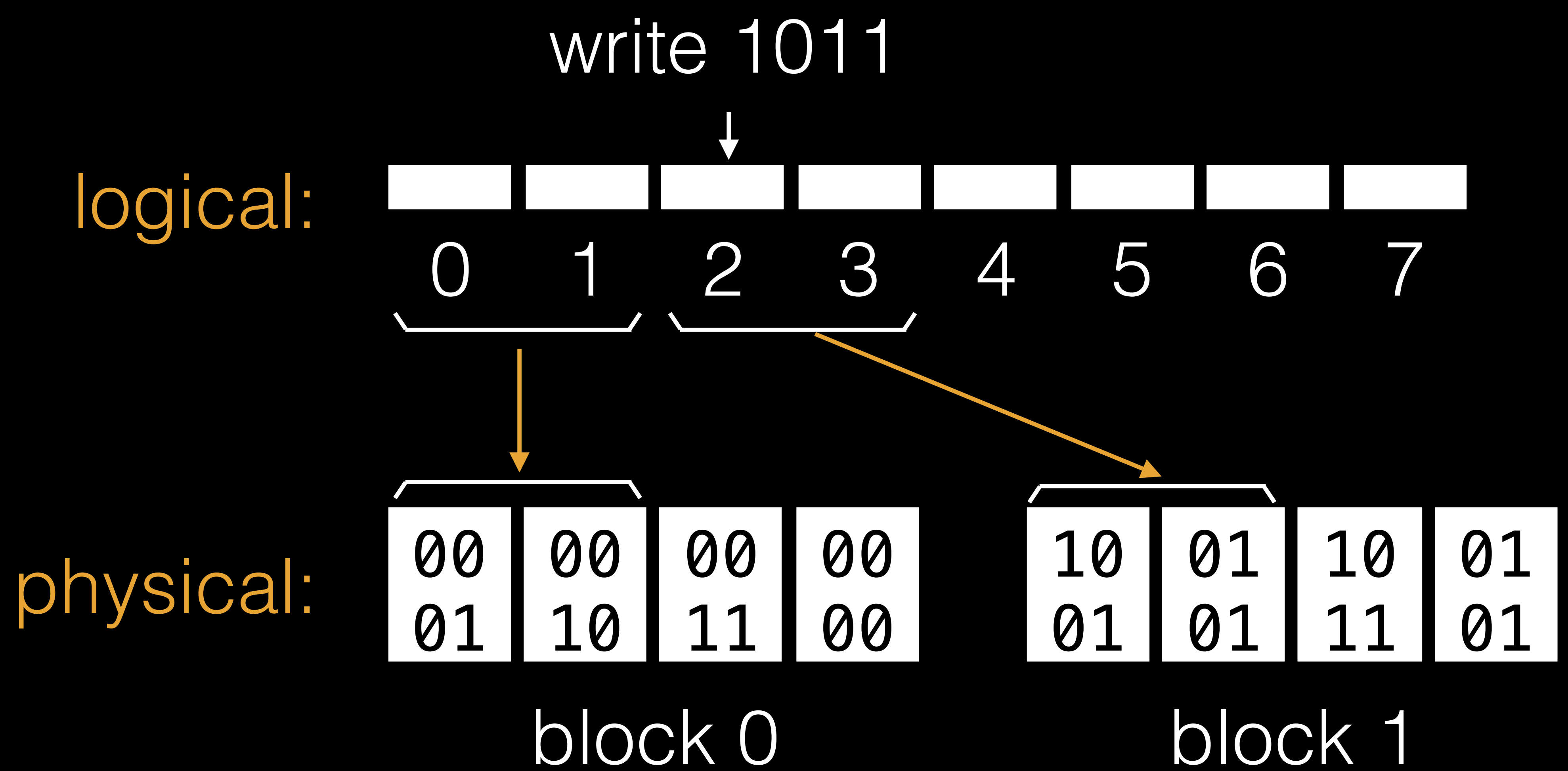
2-Page Translations



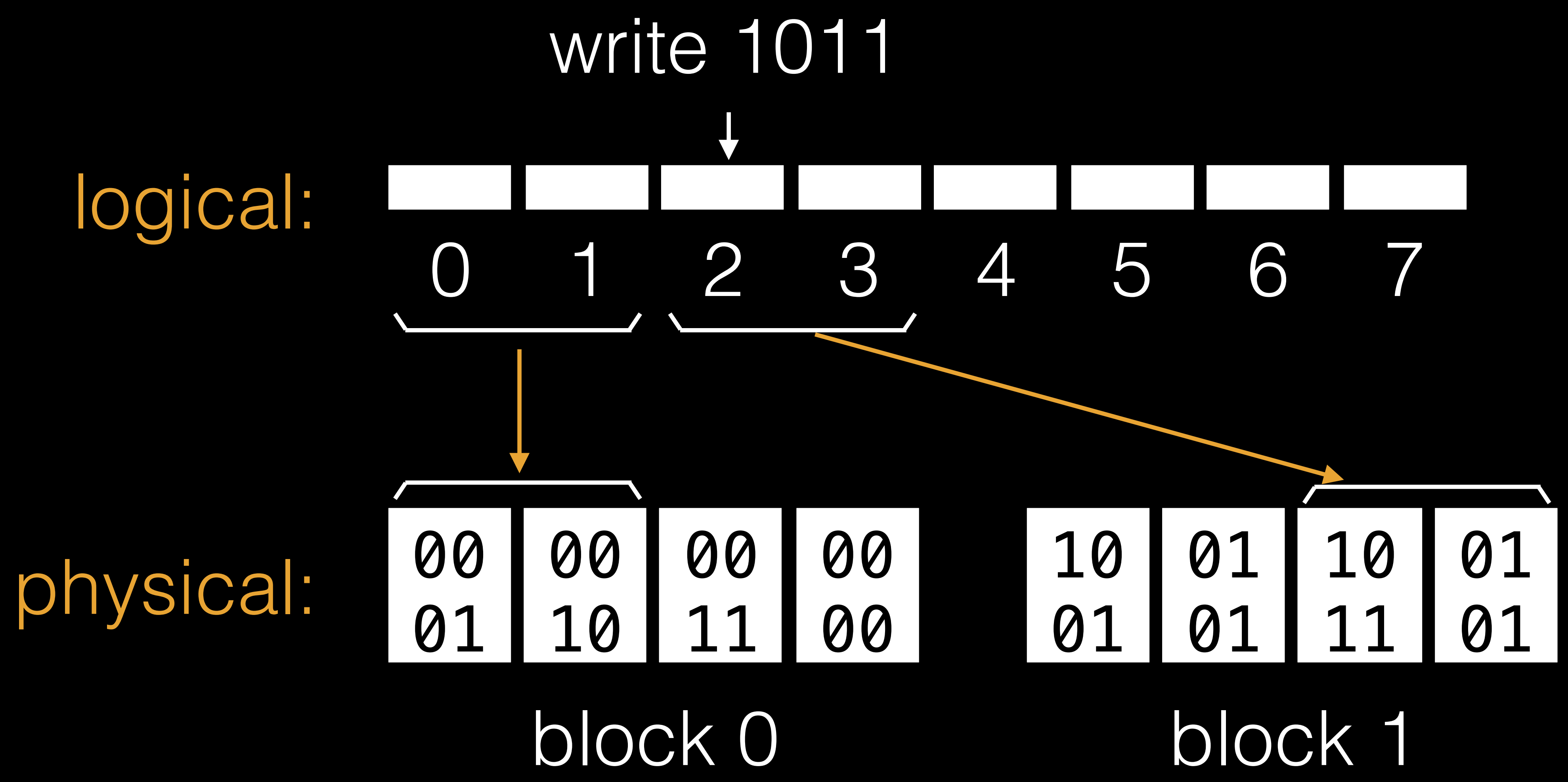
2-Page Translations



2-Page Translations



2-Page Translations



Larger Mappings

Advantage: larger mappings decrease table size.

Disadvantages?

- Increased write amplification
    - more read-modify-write updates
- more garbage
- less flexibility for placement

Hybrid FTL

Use course-grained mapping for most (e.g., 95%) of data. Map at block level.

Use fine-grained mapping for recent data. Map at page level.

Log Blocks

Write changed pages to designated log blocks.
- always search for page in these mappings first

After blocks become full, merge changes with old data.

Eventually garbage collect old pages.

Merging

Merging technique depends on I/O pattern.

Three merge types:
 - full merge
 - partial merge
 - switch merge

Merging

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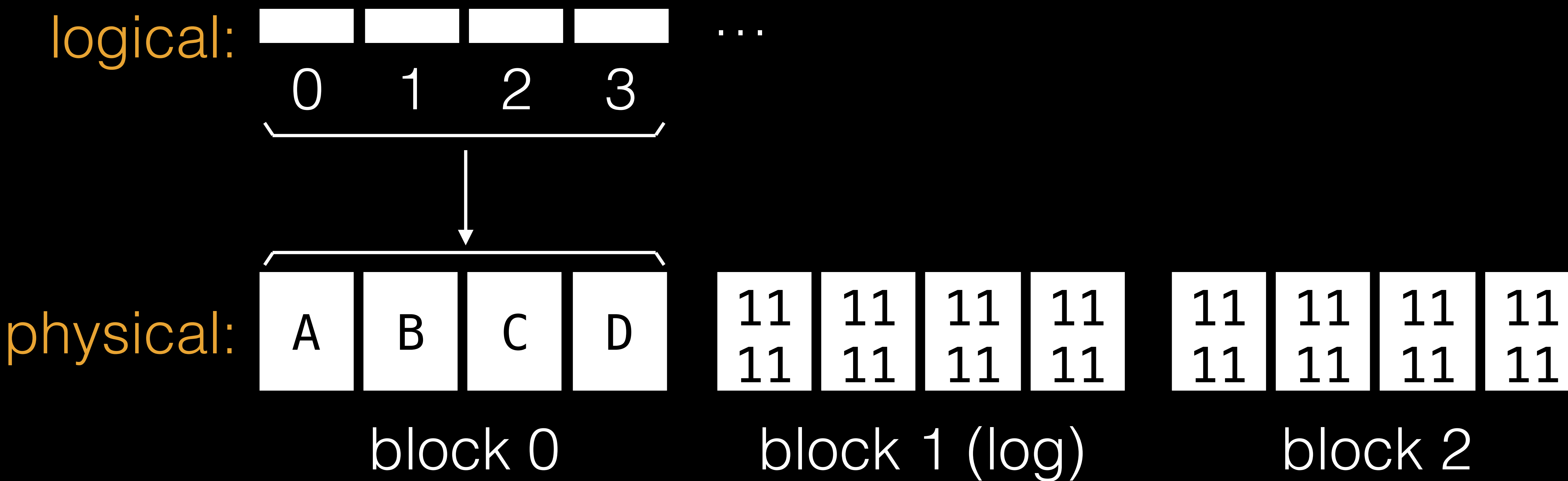
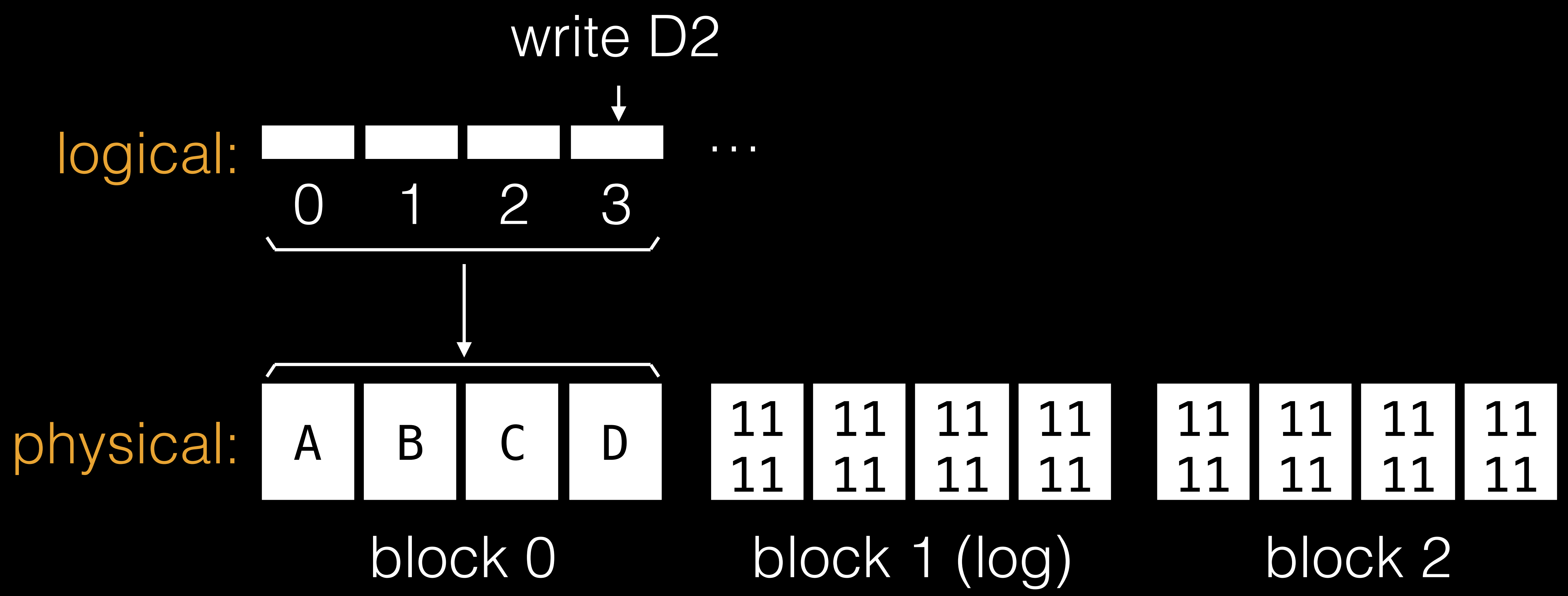
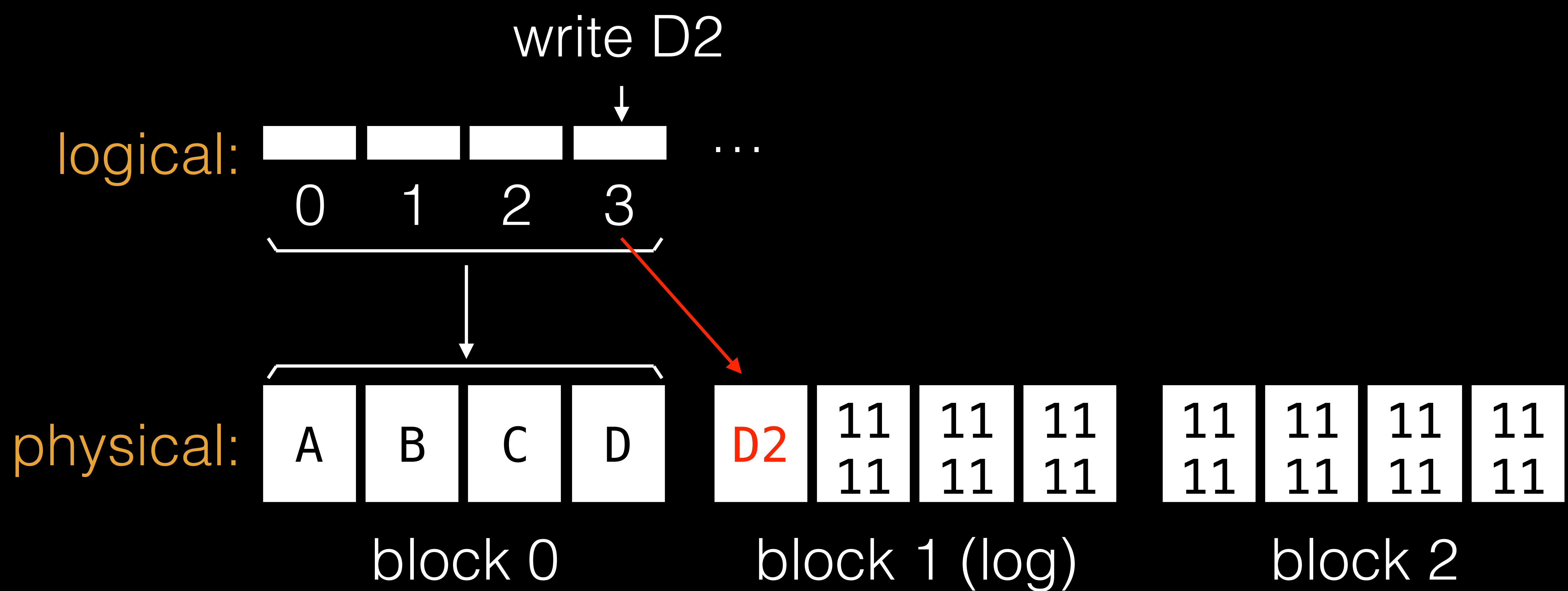
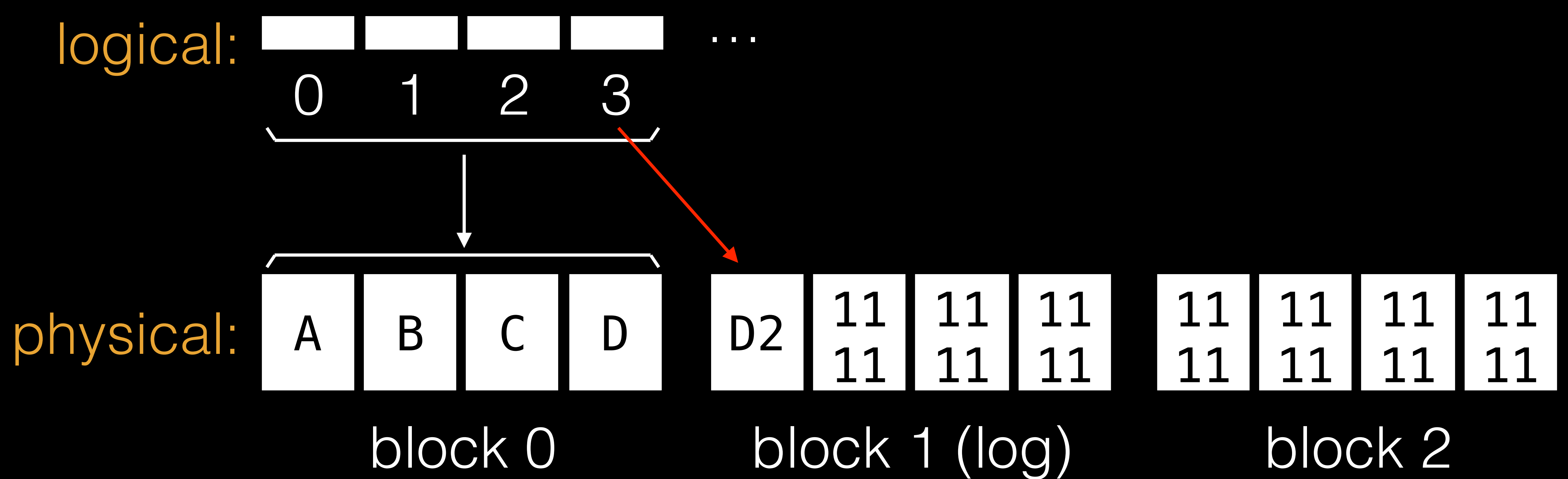


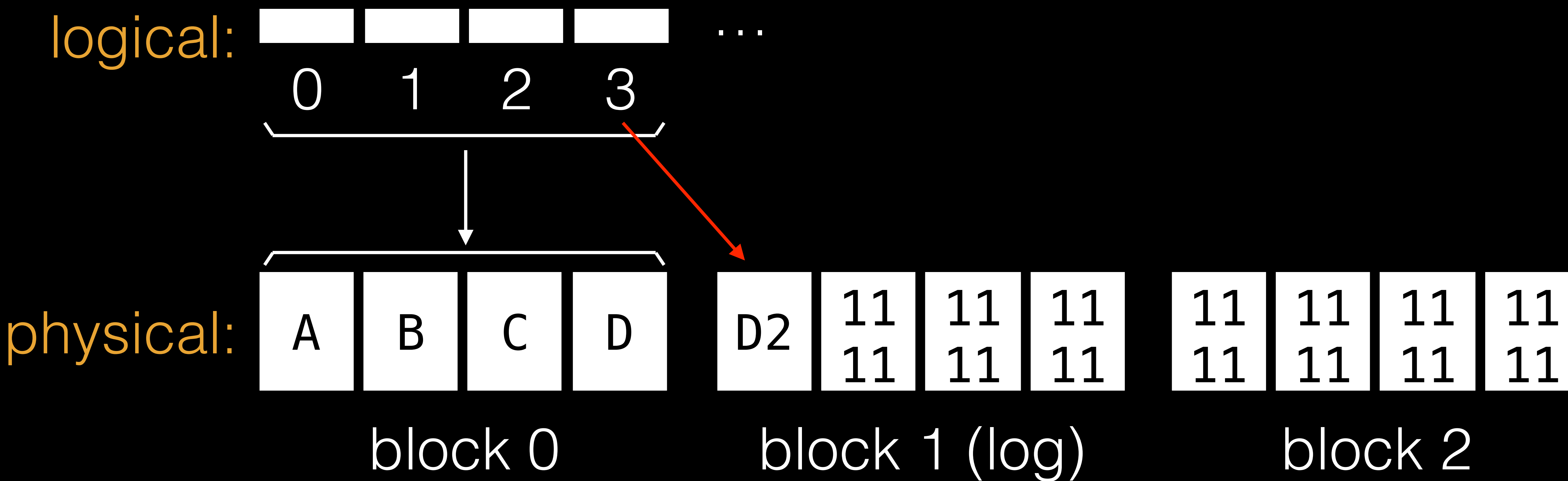
logical:
...
0
1
2
3
physical:
A
B
C
D
11 11
11 11
11 11
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2



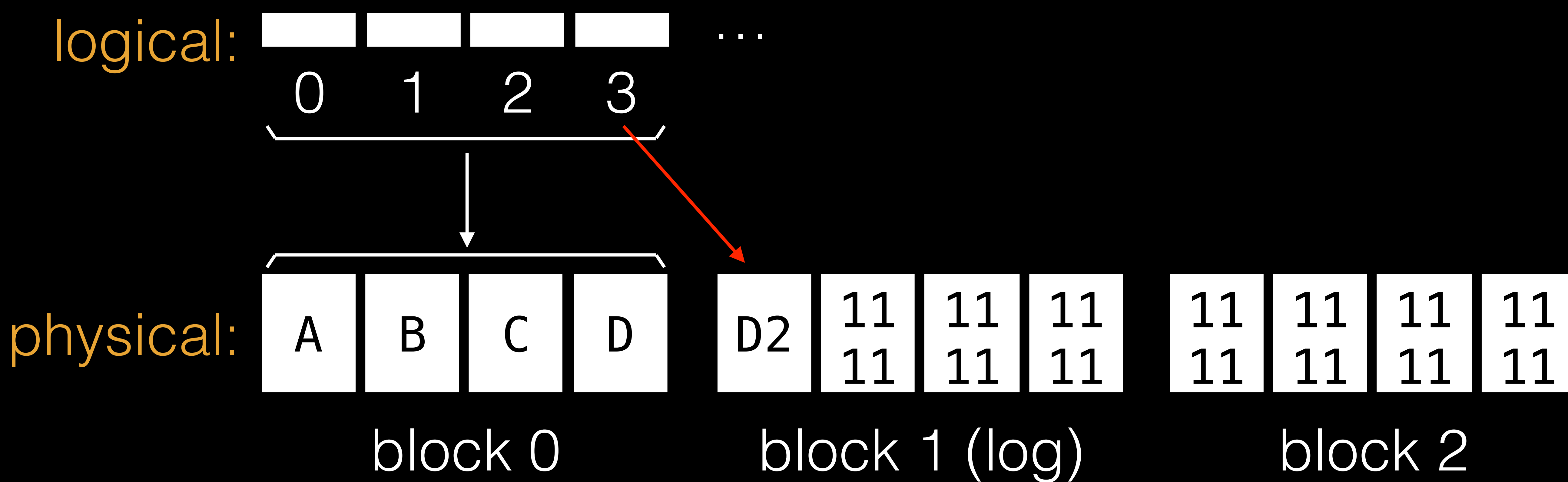
write D2
logical:
0
1
2
3
...
physical:
A
B
C
D
11 11
11 11
11 11
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


write D2
logical:
0
1
2
3
...
physical:
A
B
C
D
D2
11
11
block 0
block 1 (log)
block 2


logical:
...
0
1
2
3
physical:
A
B
C
D
D2
11 11
11 11
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2



eventually, we need to get rid of red arrows,
as these represent expensive mappings



logical:
0
1
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3
...
physical:
A
B
C
D
D2
11
11
11
11
11
11
11
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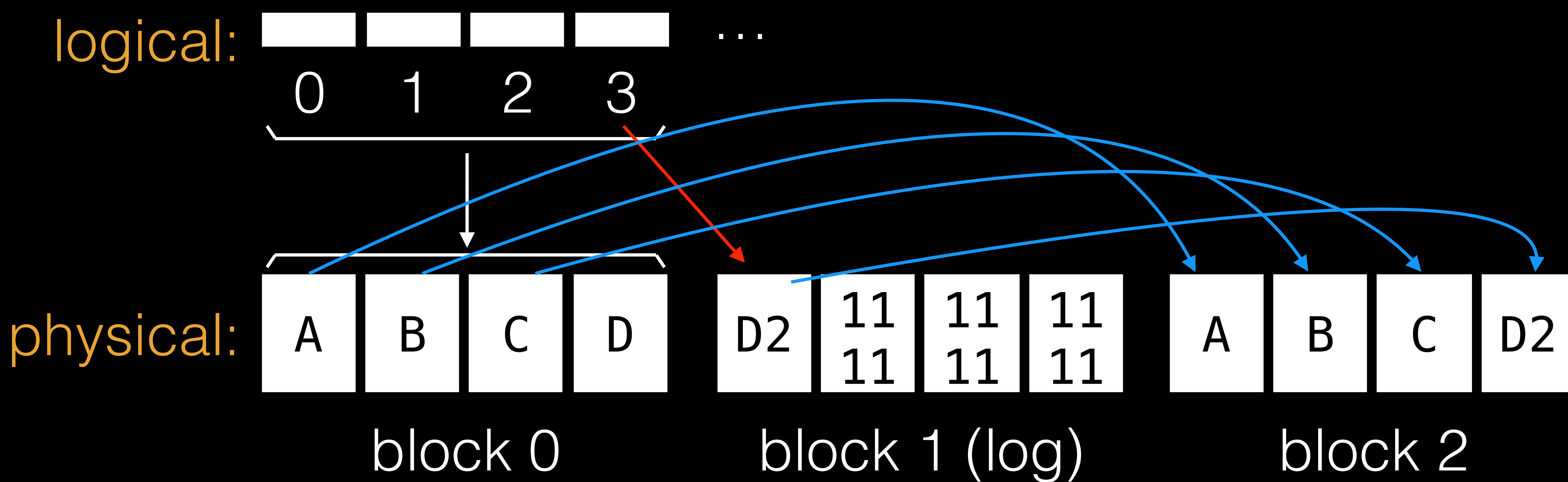
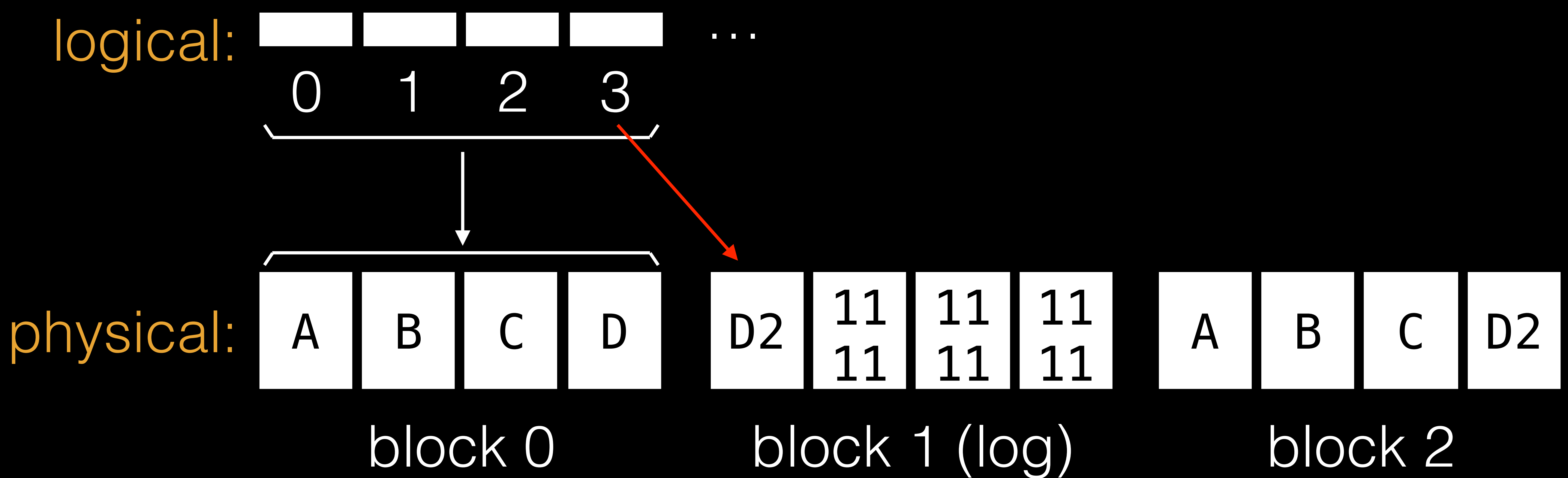
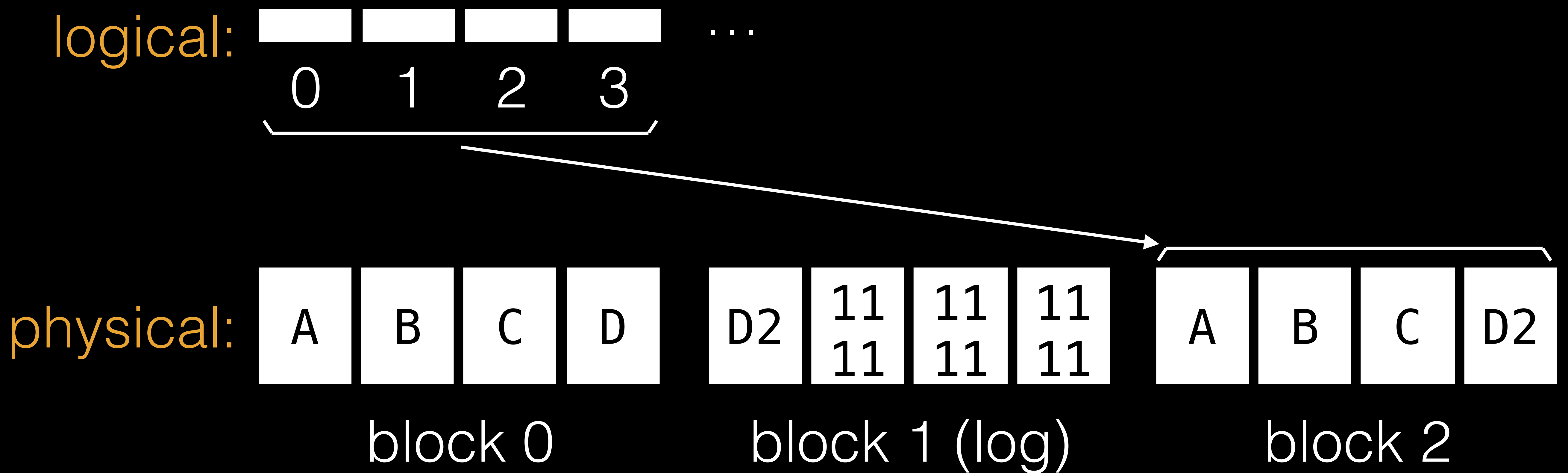
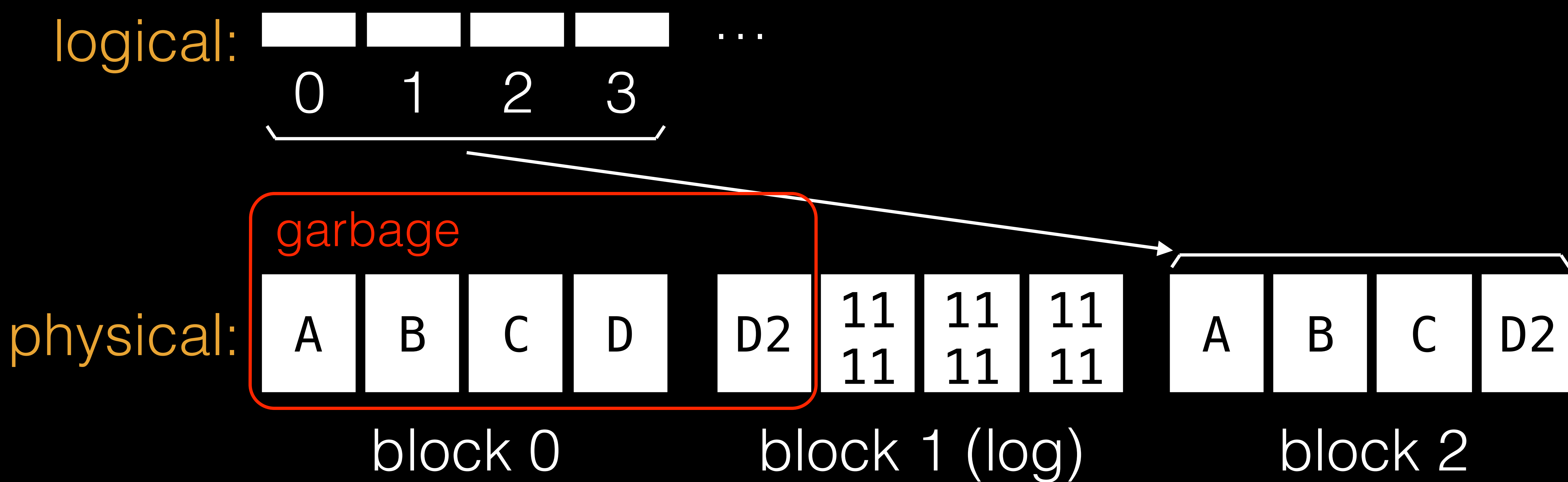
11
11
11
11
11
11
block 0
block 1 (log)
block 2



logical:
0
1
2
3
...
physical:
A
B
C
D
D2
11 11
11 11
11 11
A
B
C
D2
block 0
block 1 (log)
block 2


logical:
...
0
1
2
3
physical:
A
B
C
D
D2
11
11
11
11
11
11
A
B
C
D2
block 0
block 1 (log)
block 2


logical:
0
1
2
3
...
physical:
A
B
C
D
D2
11 11
11 11
11 11
A
B
C
D2
block 0
block 1 (log)
block 2

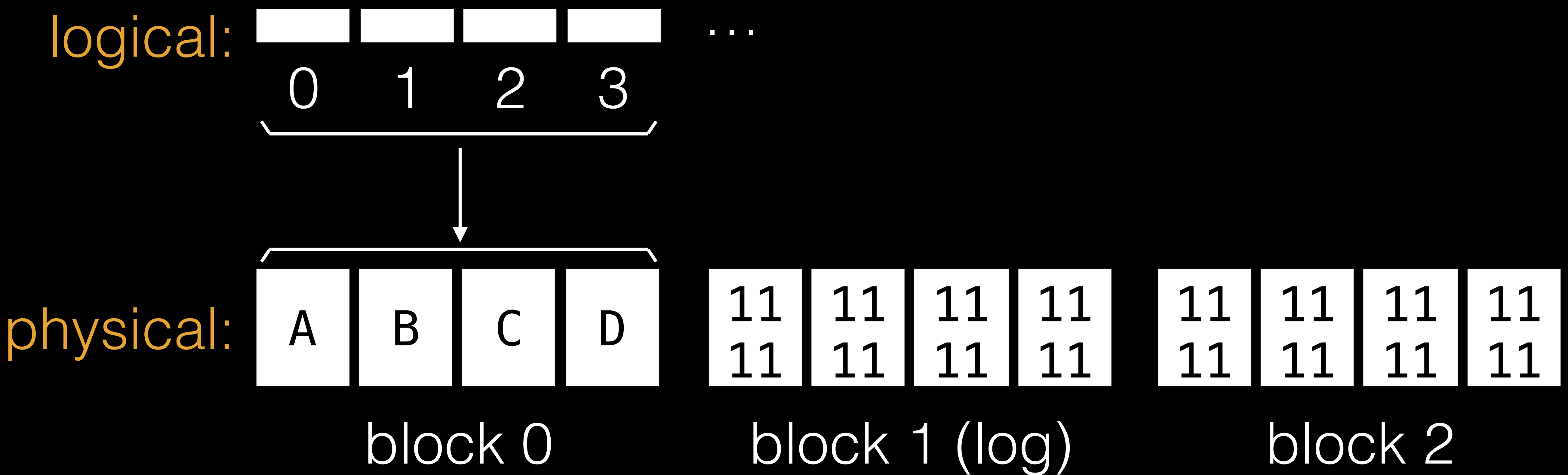


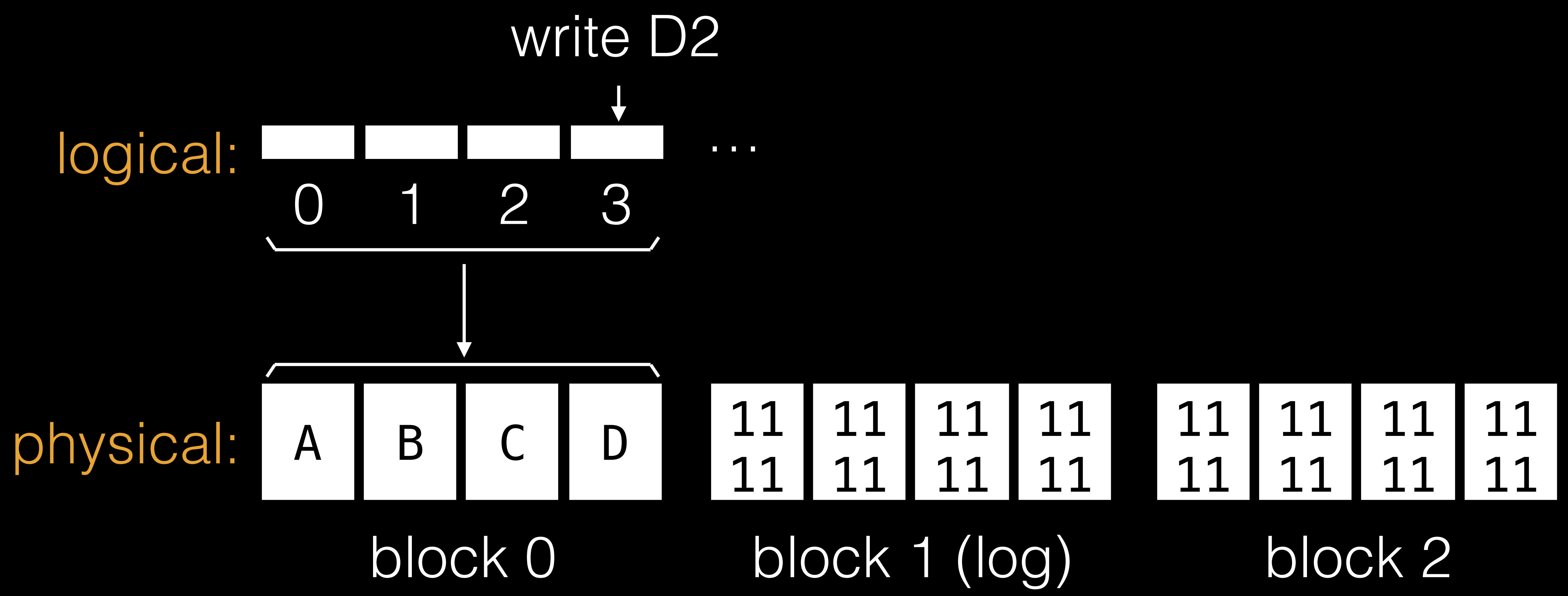
logical:
...
0
1
2
3
garbage
physical:
A
B
C
D
D2
11
11
11
11
11
11
A
B
C
D2
block 0
block 1 (log)
block 2

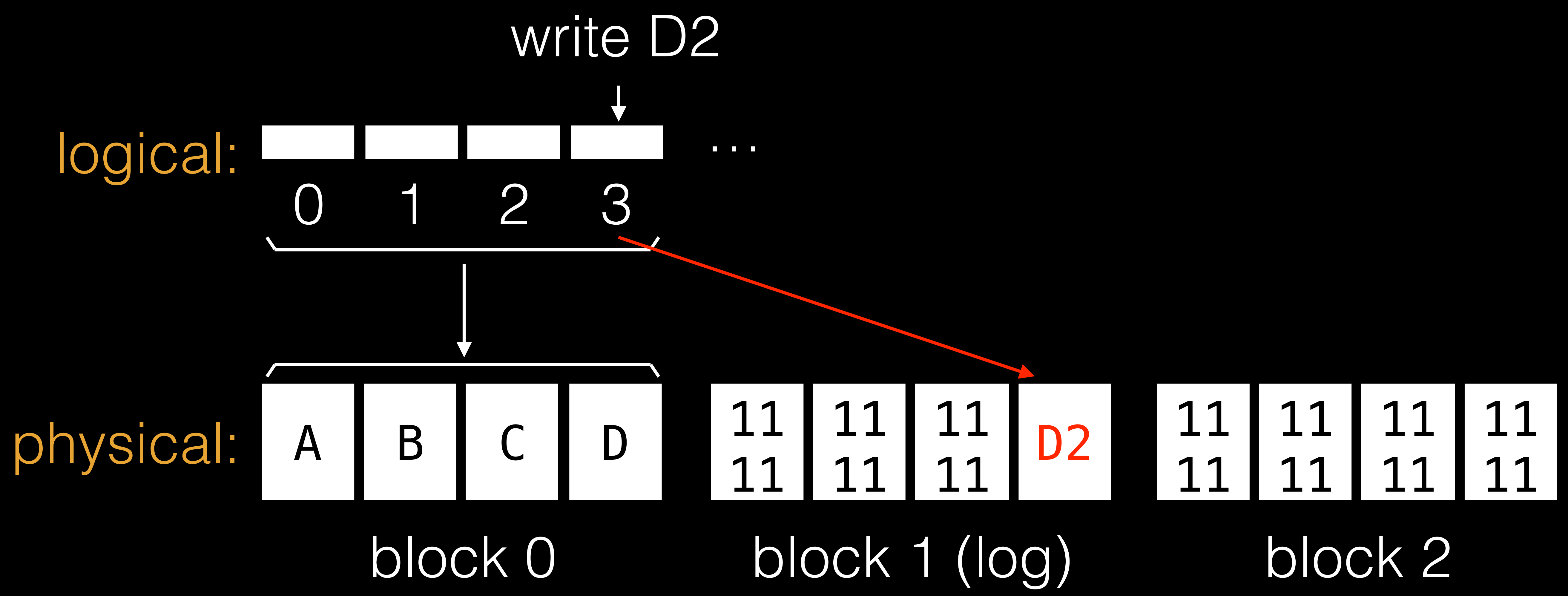
Merging

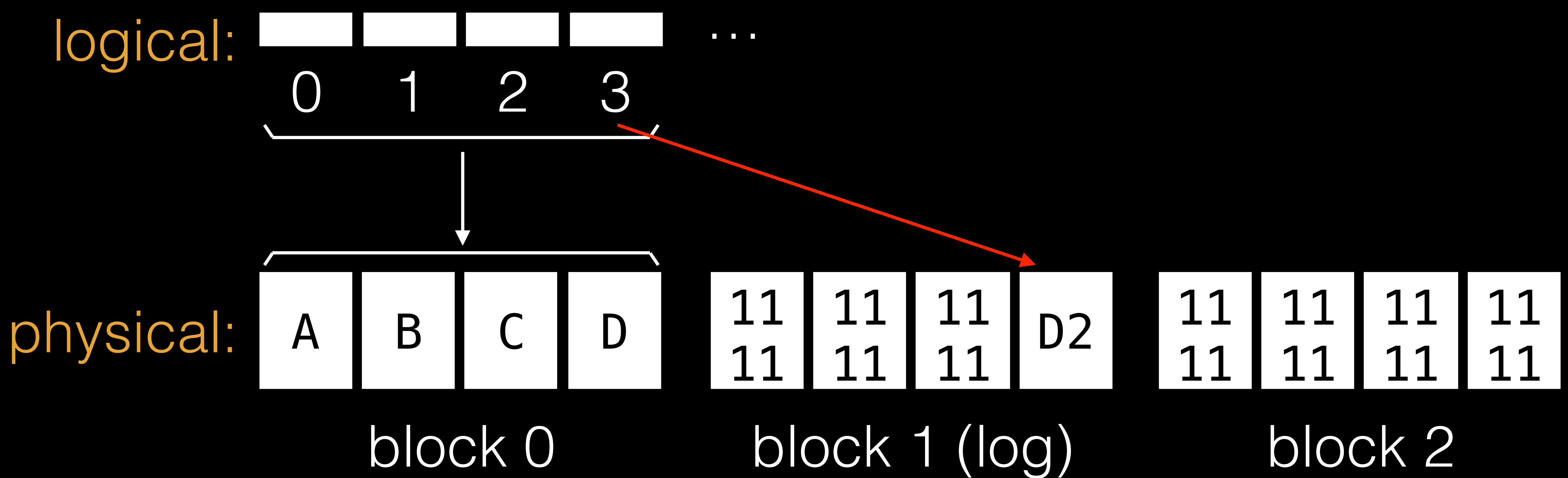
Merging technique depends on I/O pattern.

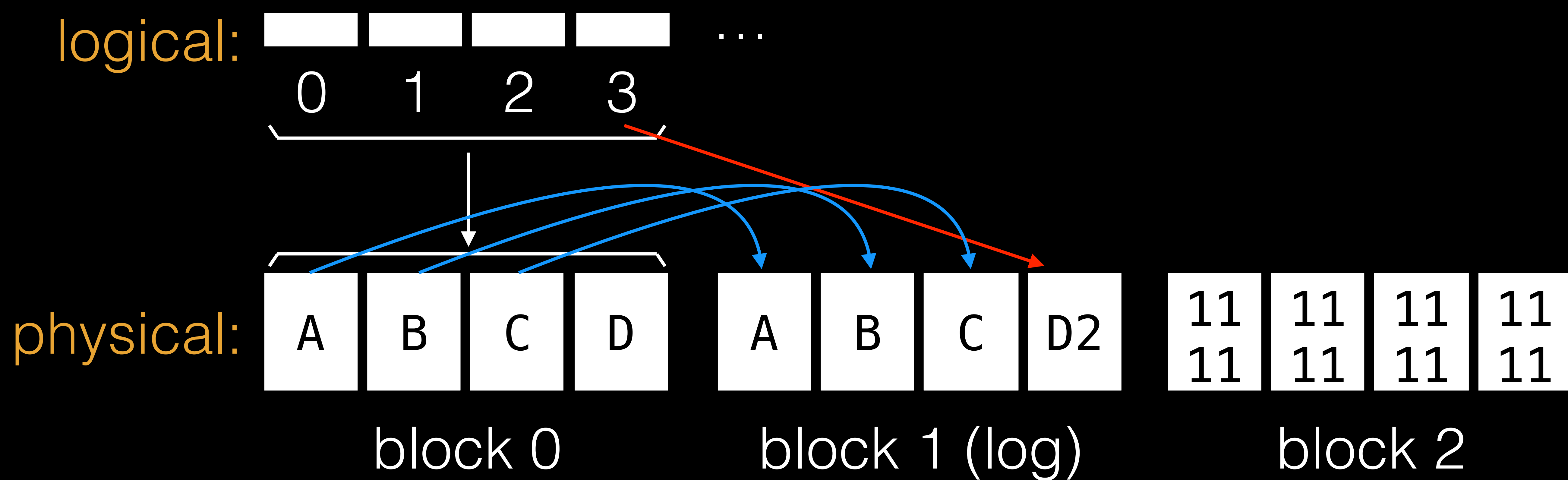
Three merge types:
- full merge
- partial merge
- switch merge

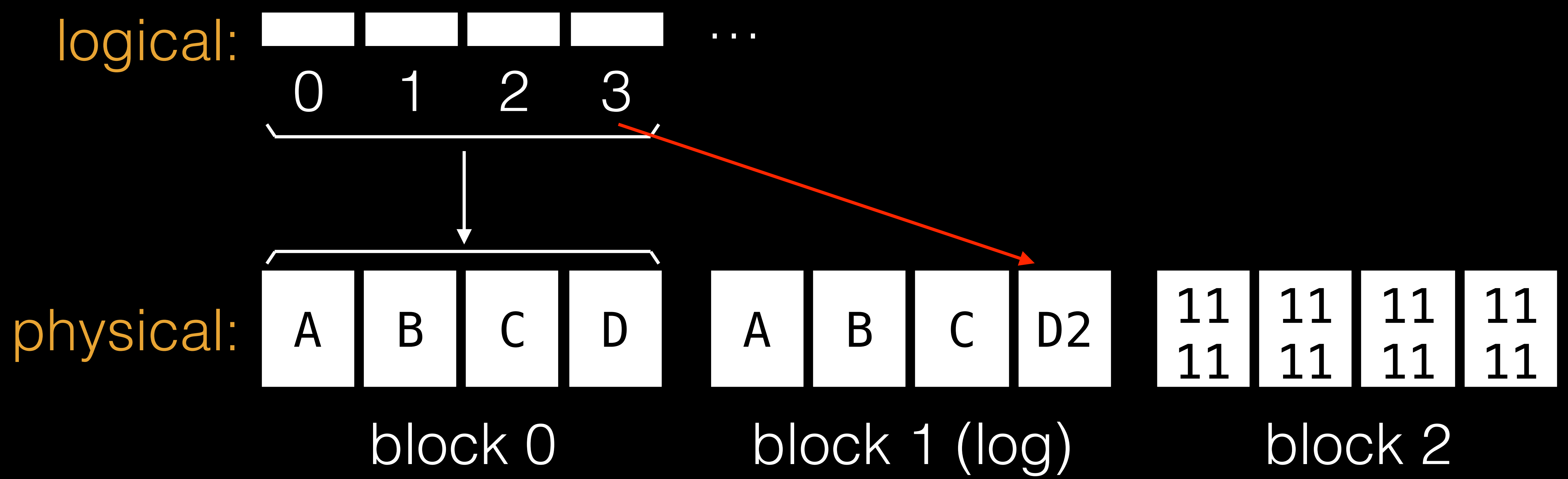

logical:
0
1
2
3
...
physical:
A
B
C
D
11 11
11 11
11 11
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


write D2
logical:
0
1
2
3
...
physical:
A
B
C
D
11 11
11 11
11 11
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


write D2
logical:
0
1
2
3
...
physical:
A
B
C
D
11 11
11 11
11 11
D2
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


logical:
...
0
1
2
3
physical:
A
B
C
D
11 11
11 11
11 11
D2
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


logical:
...
0
1
2
3
physical:
A
B
C
D
A
B
C
D2
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


logical:
...
0
1
2
3
physical:
A
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C
D
A
B
C
D2
11 11
11 11
11 11
11 11
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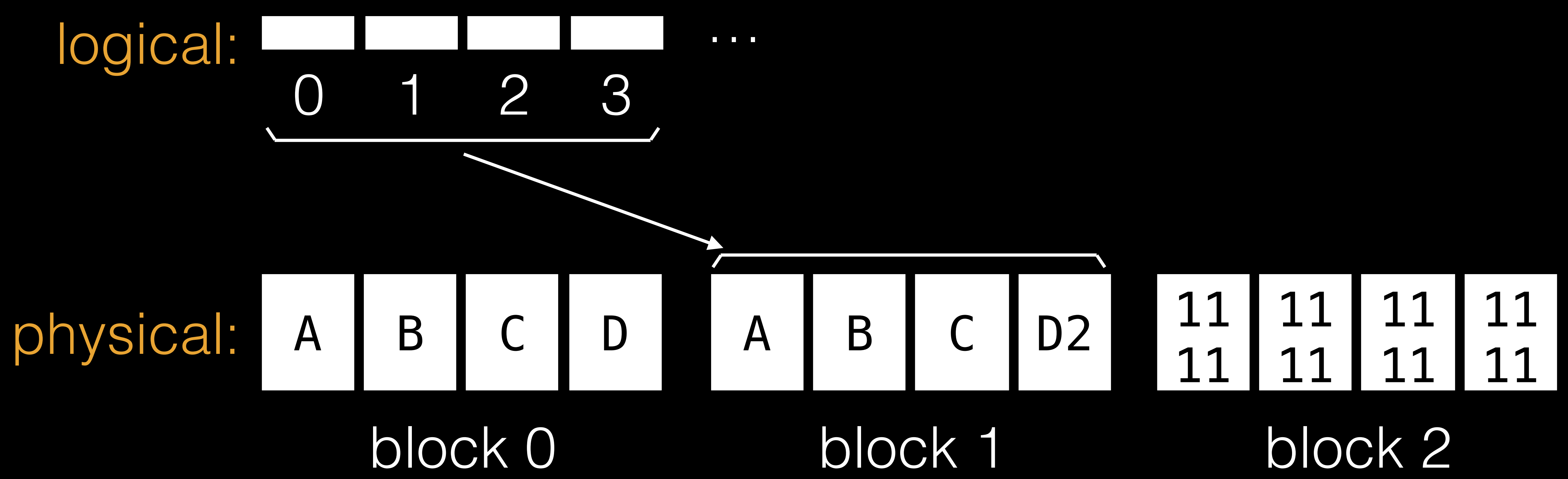
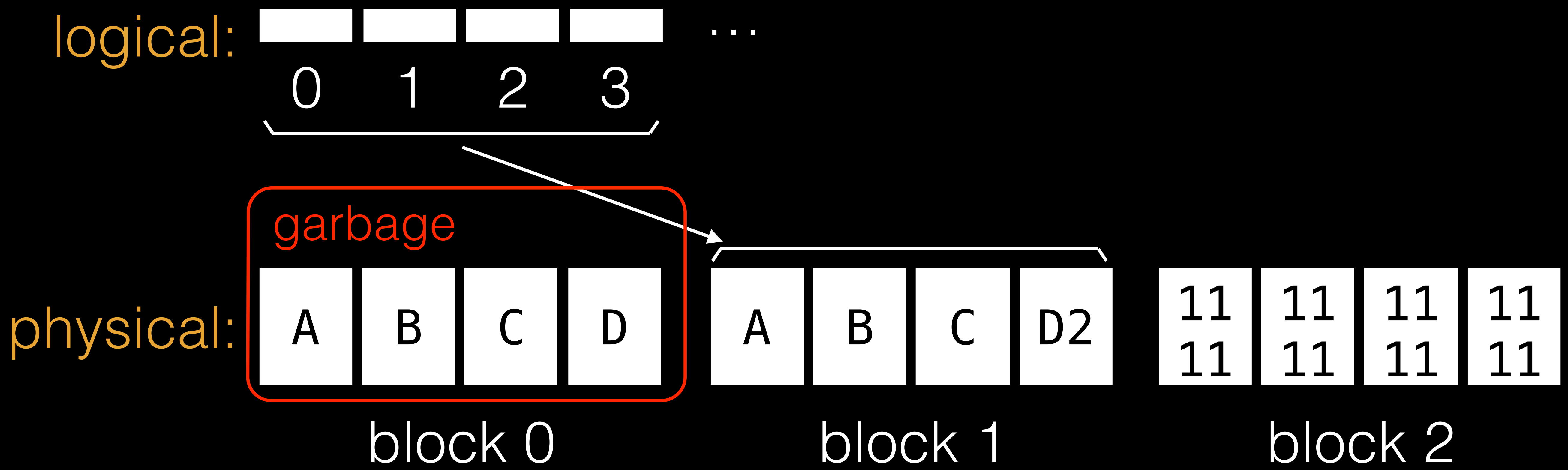
block 2


logical:
...
0
1
2
3
physical:
A
B
C
D
A
B
C
D2
11 11
11 11
11 11
11 11
block 0
block 1
block 2



logical:
0
1
2
3
...
garbage
physical:
A
B
C
D
A
B
C
D2
11 11
11 11
11 11
11 11
block 0
block 1
block 2

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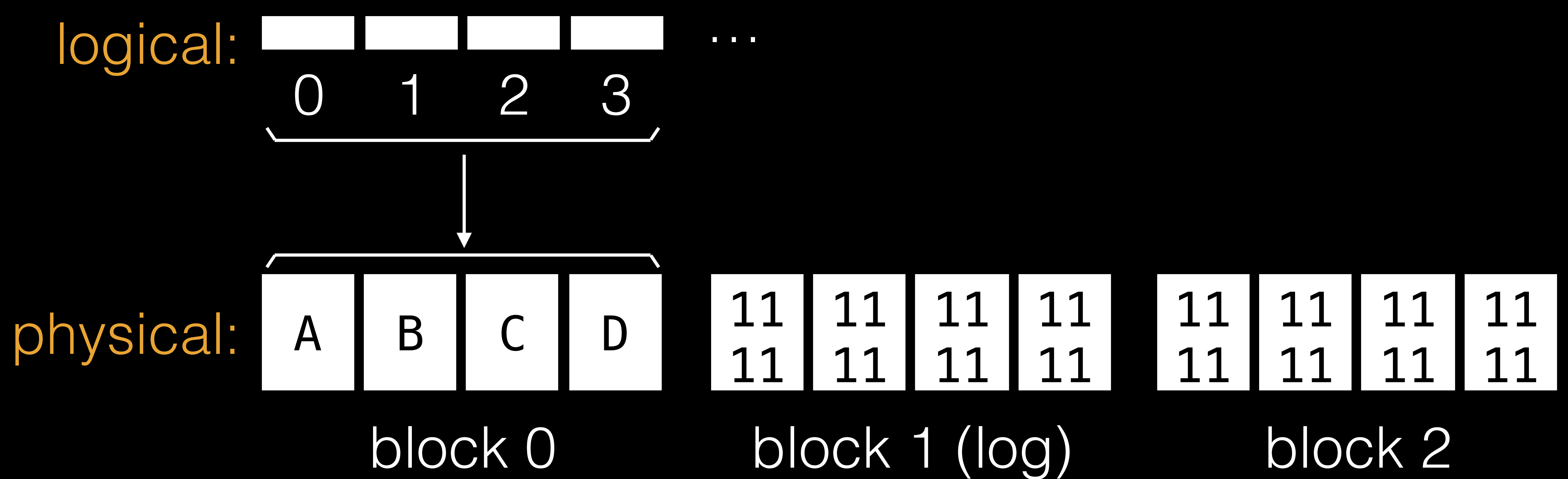
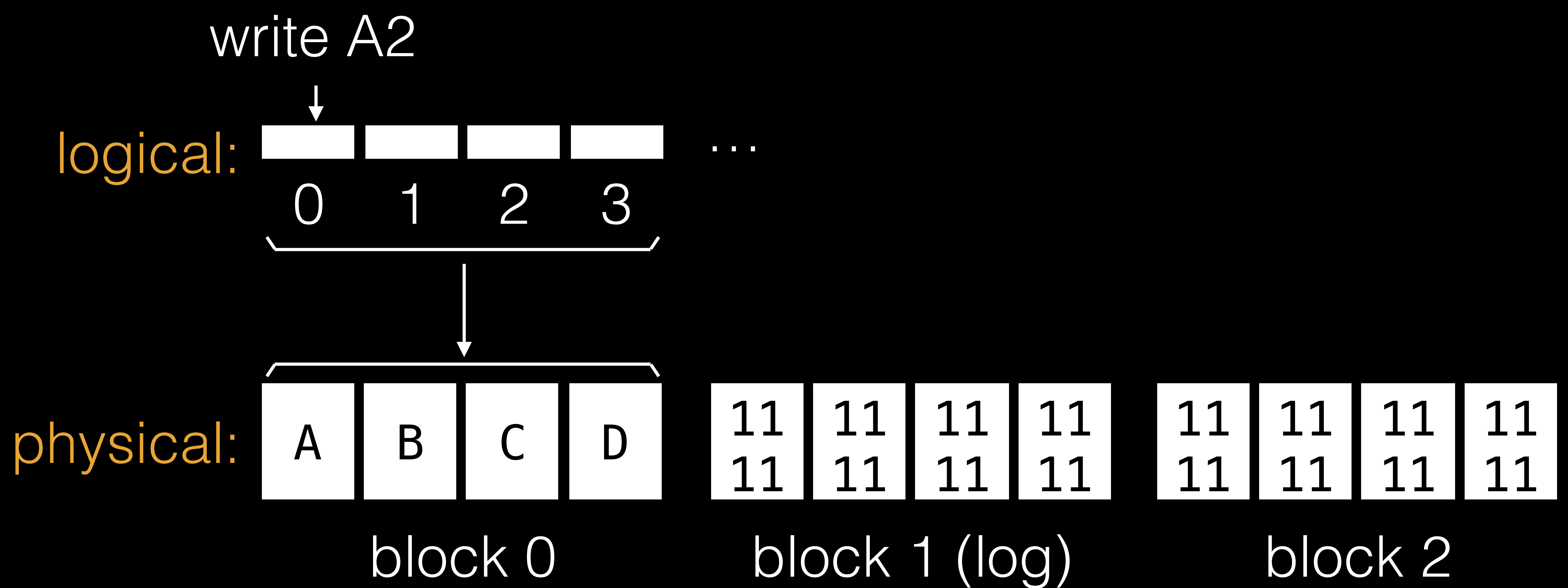
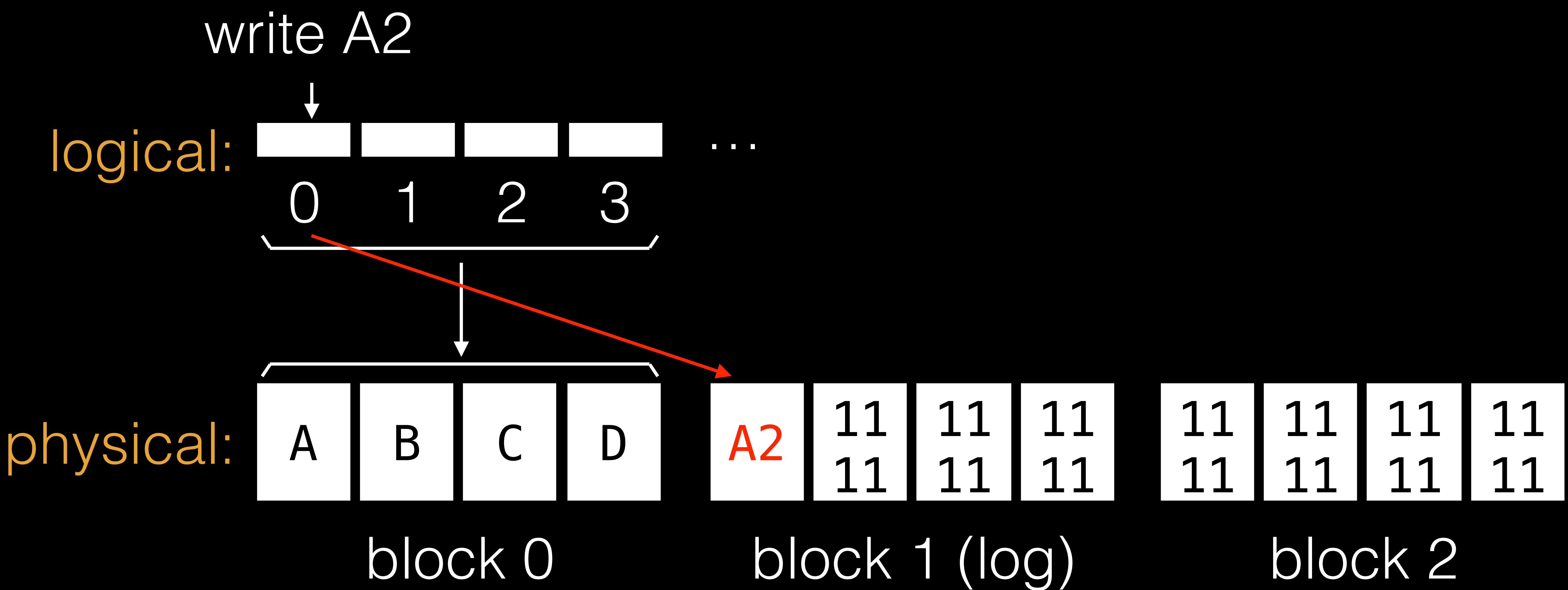


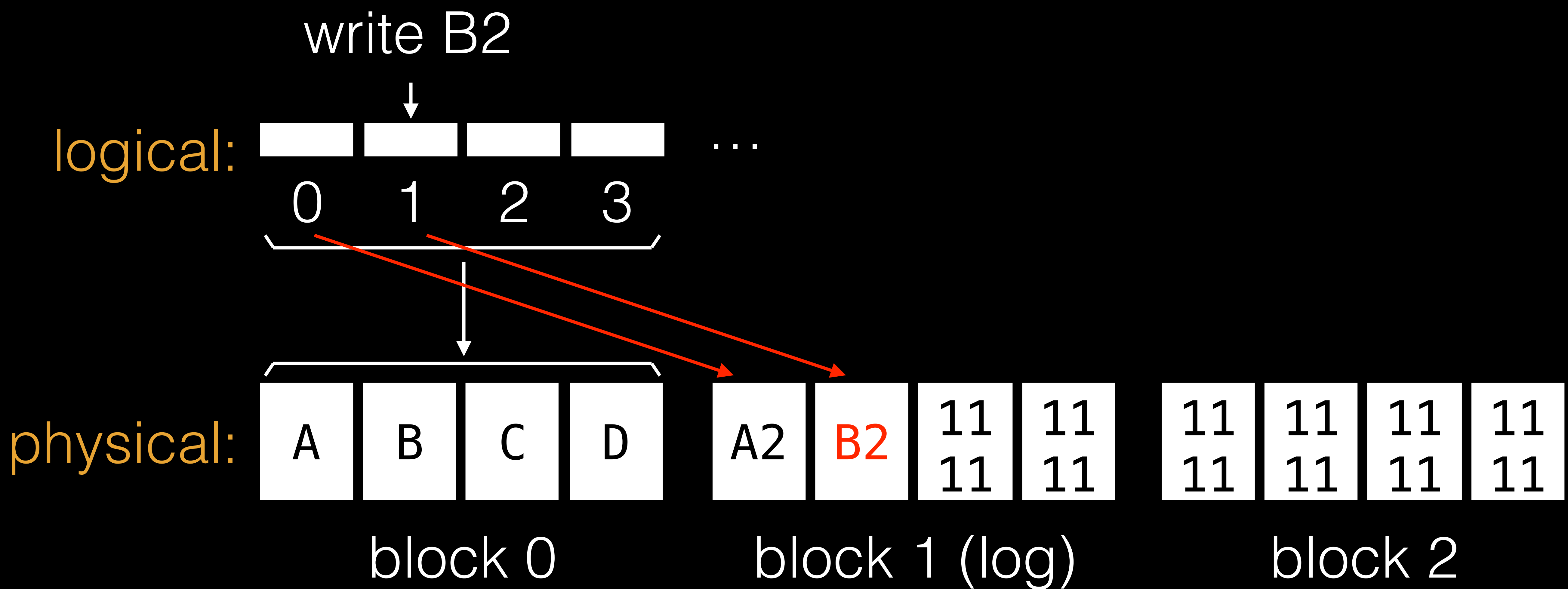
logical:
...
0
1
2
3
physical:
A
B
C
D
11 11
11 11
11 11
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2

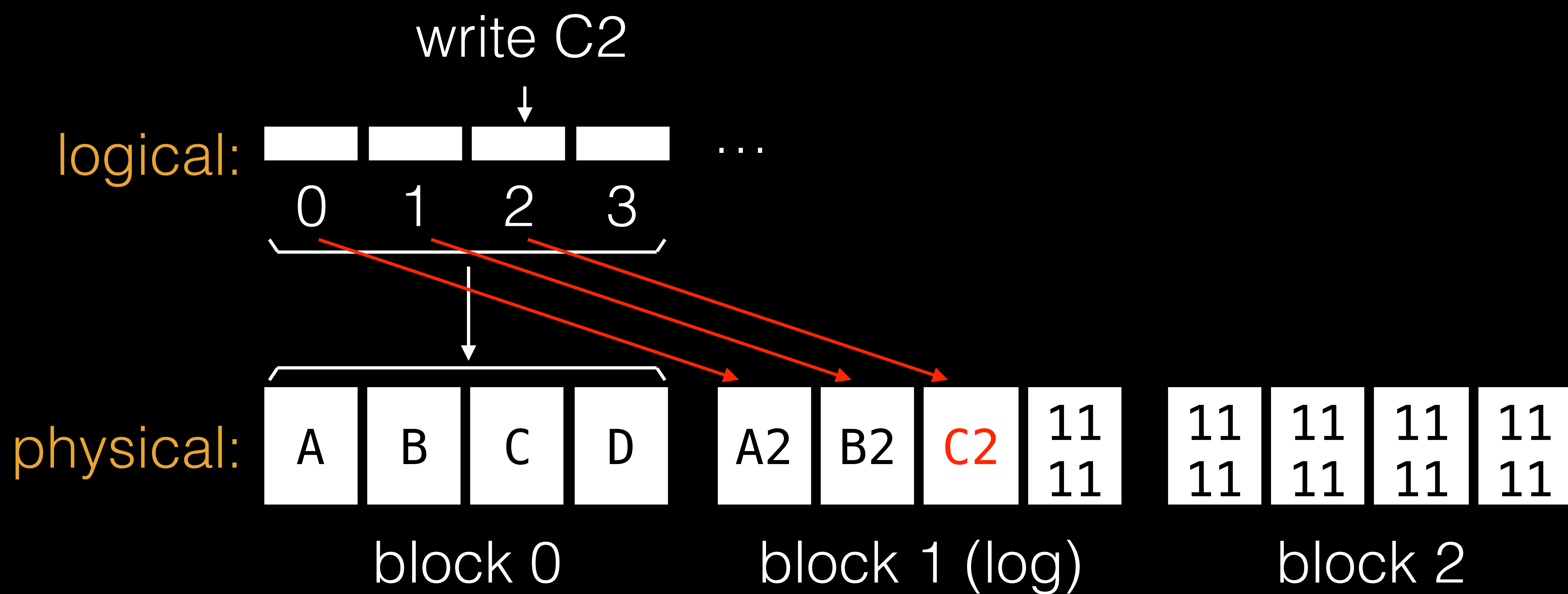


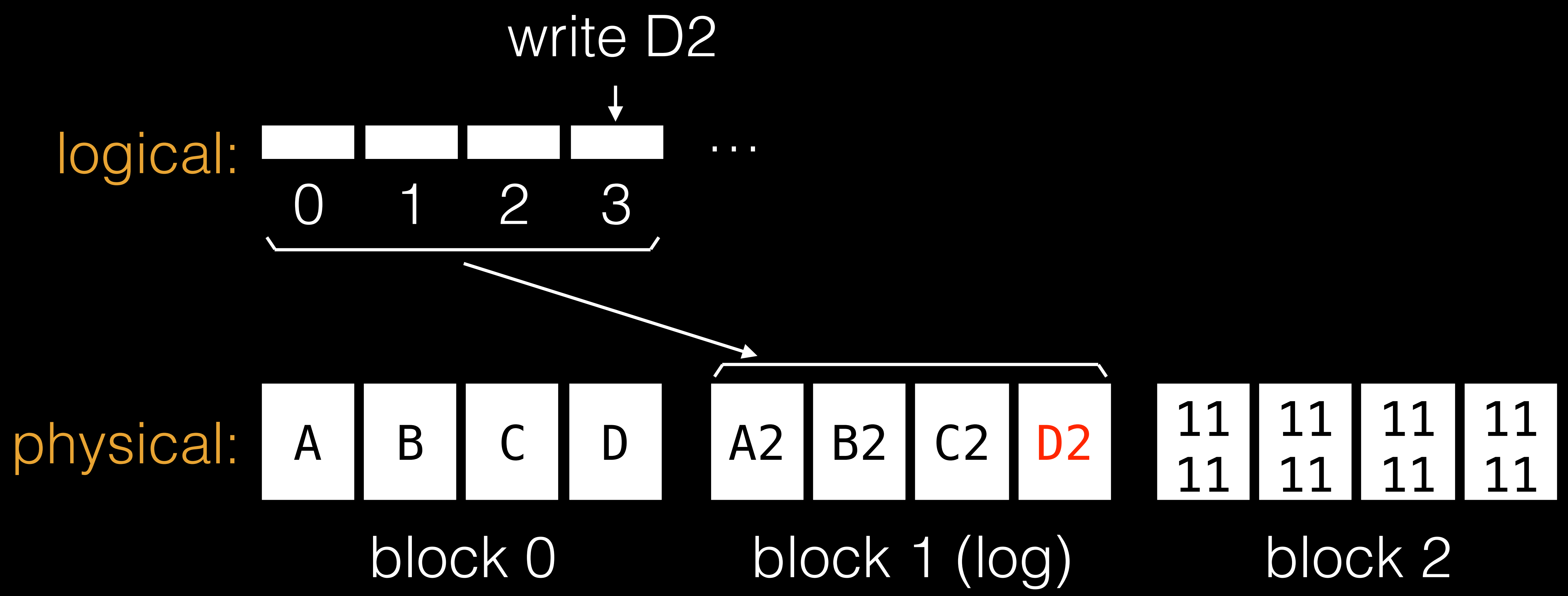
write A2
logical:
...
0
1
2
3
physical:
A
B
C
D
11
11
11
11
11
11
11
11
11
11
11
11
11
11
11
11
block 0
block 1 (log)
block 2

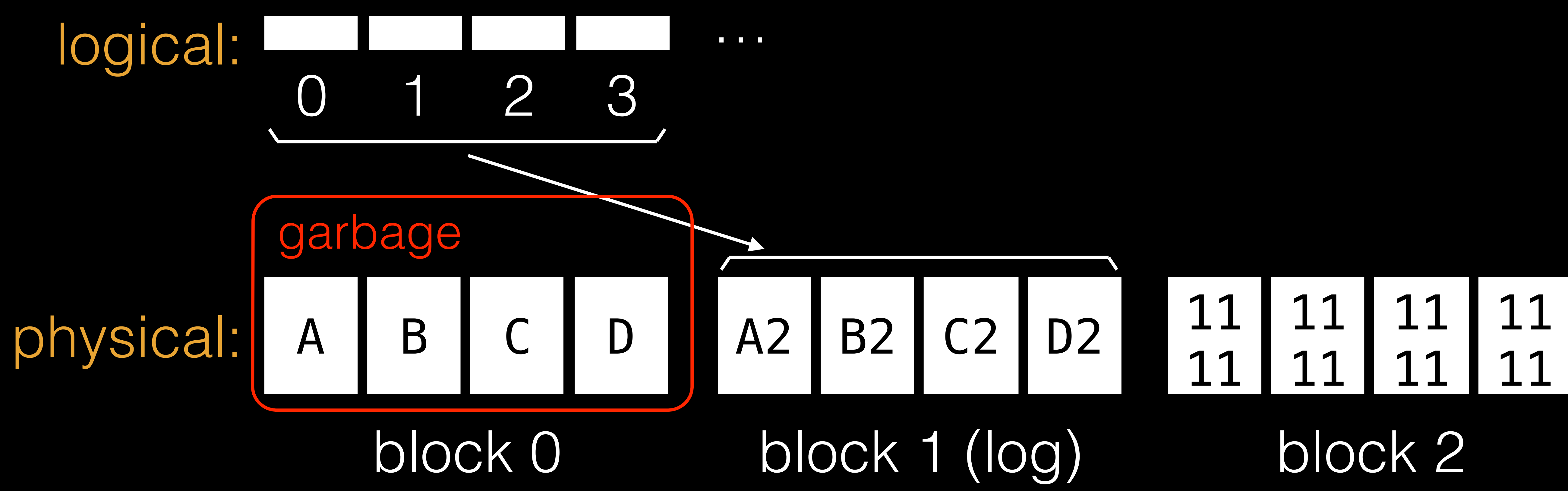


write A2
logical:
...
0
1
2
3
physical:
A
B
C
D
A2
11 11
11 11
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


write B2
logical:
0
1
2
3
...
physical:
A
B
C
D
A2
B2
11 11
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


write C2
logical:
0
1
2
3
...
physical:
A
B
C
D
A2
B2
C2
11 11
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


write D2
logical:
0
1
2
3
...
physical:
A
B
C
D
A2
B2
C2
D2
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2


logical:
...
0
1
2
3
garbage
physical:
A
B
C
D
A2
B2
C2
D2
11 11
11 11
11 11
11 11
block 0
block 1 (log)
block 2

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Merging technique depends on I/O pattern.

Three merge types:

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- partial merge
- switch merge

Summary

Flash is much faster than disk, but…

It is more expensive.

It's not a drop-in replacement beneath an FS without a complex layer for emulating hard disk API.