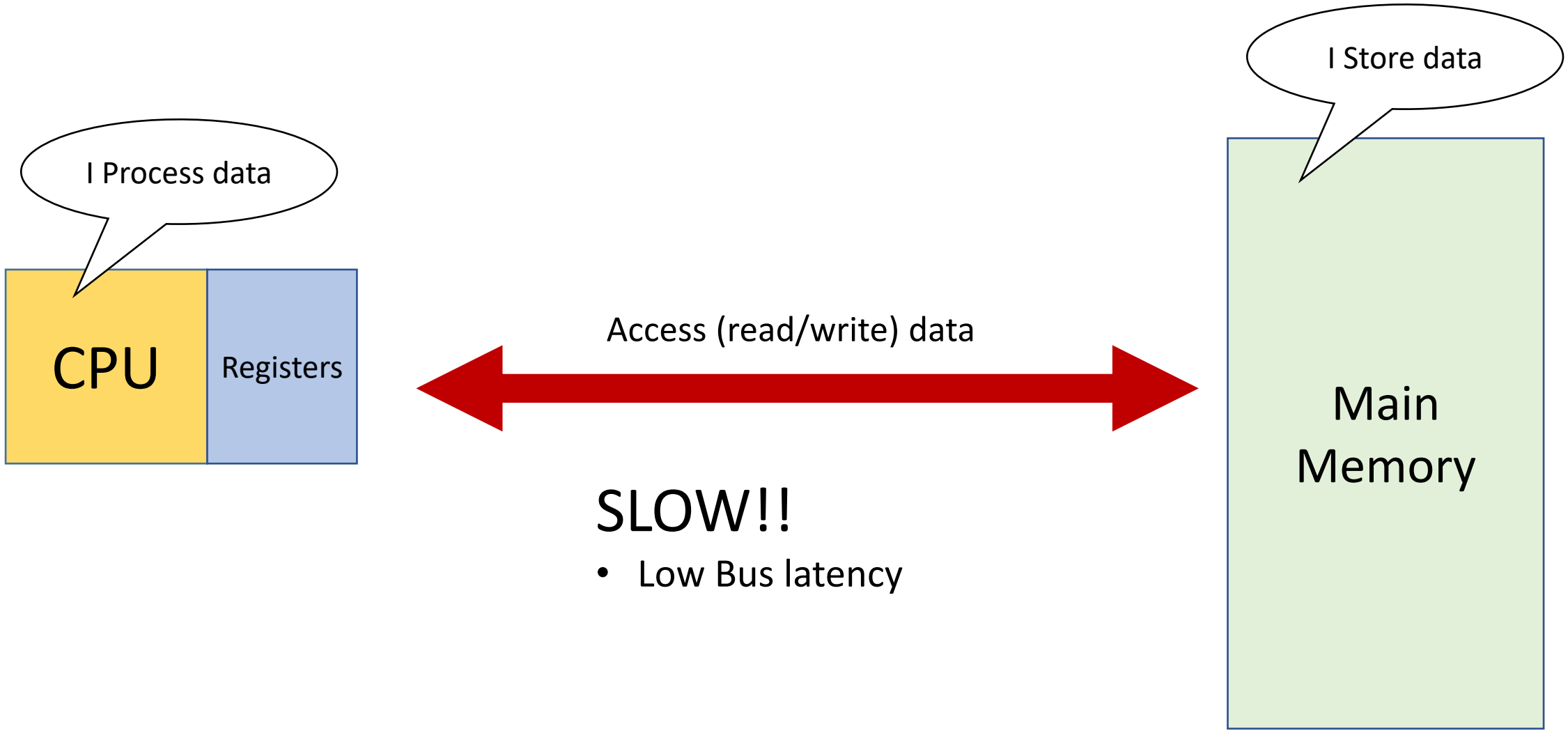
Cache Memory

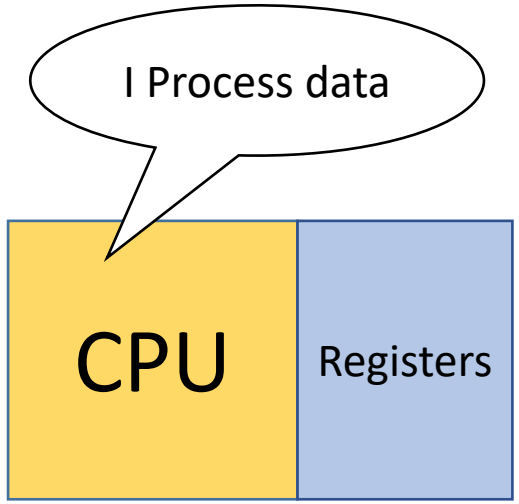
From what we know until now

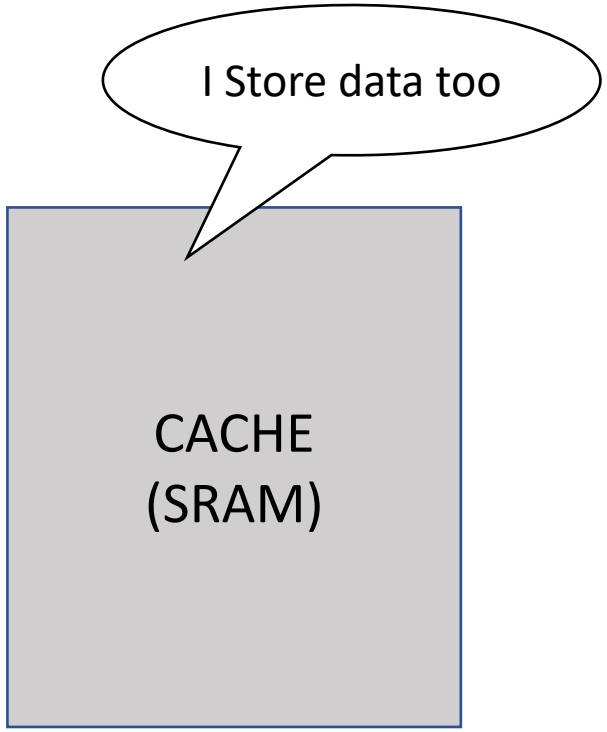


SLOW!!

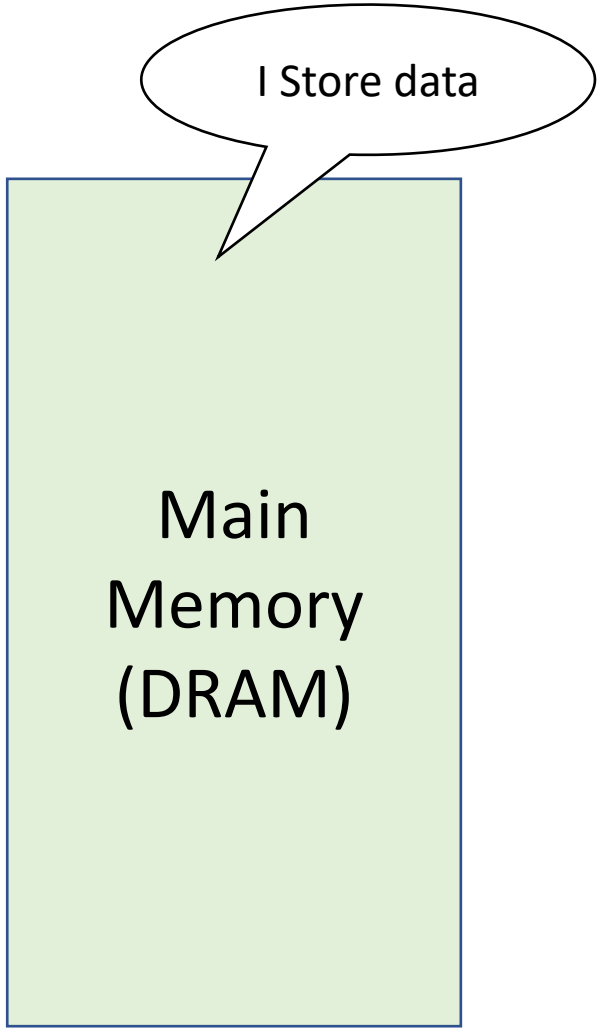
- Low Bus latency

Solution – Cache Memory



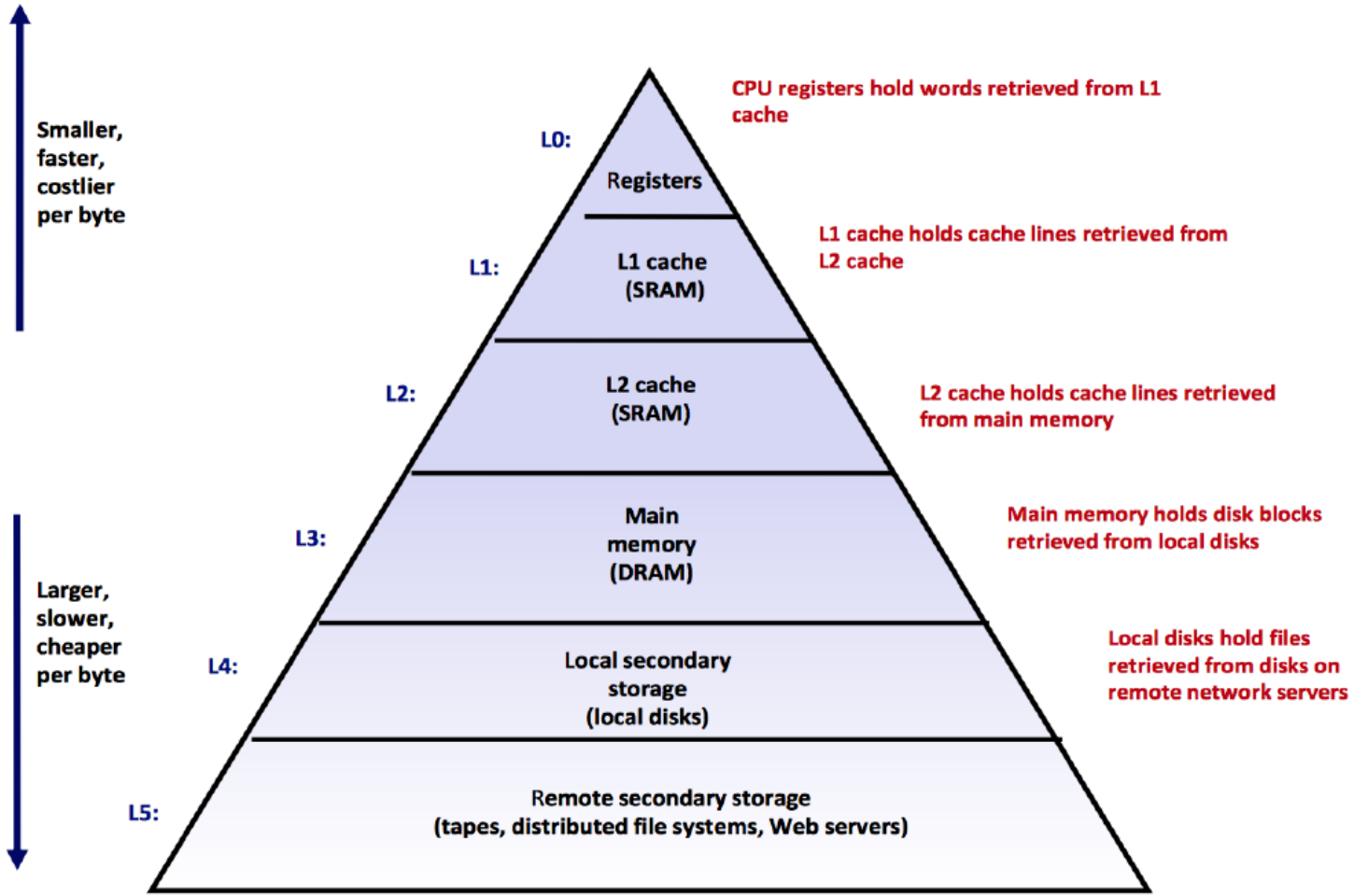


+ FASTER!!
+ Closer to Processor
– More Expensive
– Smaller Capacity



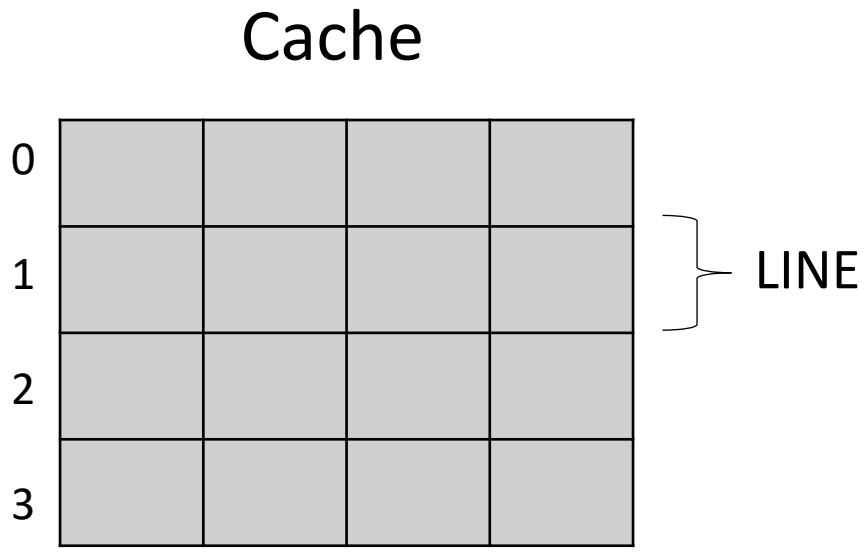
– SLOWER
– Far from Processor
+ Cheaper
+ Larger Capacity

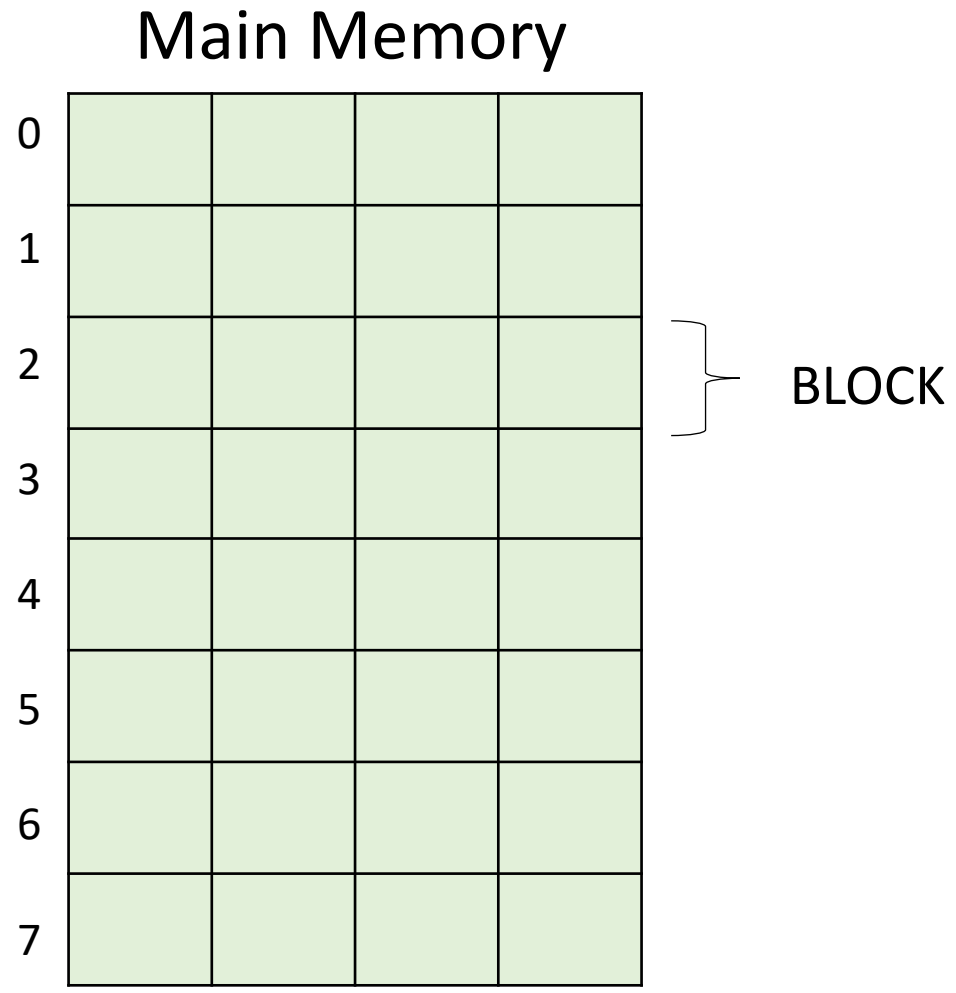
Memory Hierarchy



https://slidetodoc.com/carnegie-mellon-the-memory-hierarchy-15-213-introduction/

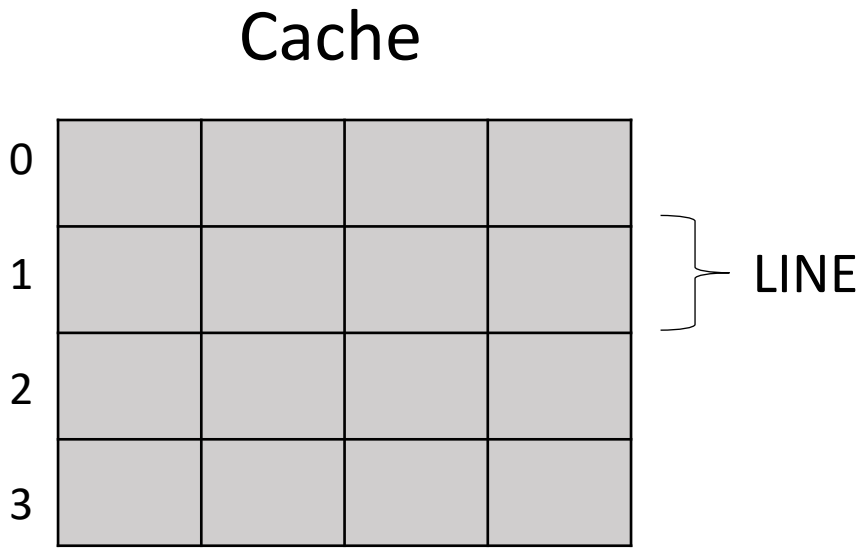
Looking Inside Cache and Main Memory





A collection of Cache Lines is called a Cache **SET**.

Looking Inside Cache and Main Memory



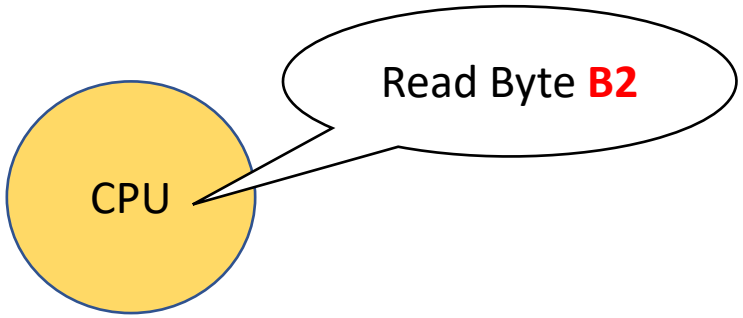
Main Memory

0	B0	B1	B2	B3
1	B4	B5	B6	B7
2	B8	B9	B10	B11
3	B12	B13	B14	B15
4	B16	B17	B18	B19
5	B20	B21	B22	B23
6	B24	B25	B26	B27
7	B28	B29	B30	B31

BLOCK

LINE SIZE = BLOCK SIZE

Accessing Data



Step 1: Search in CACHE

IF B2 exists in Cache

- **HIT**

IF B2 NOT found in Cache

- **MISS**
- Proceed to **Step 2**

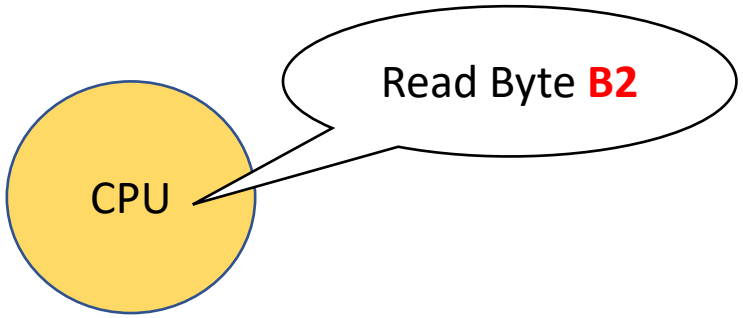
Cache

0				
1				
2				
3				

Main Memory

0	B0	B1	B2	B3
1	B4	B5	B6	B7
2	B8	B9	B10	B11
3	B12	B13	B14	B15
4	B16	B17	B18	B19
5	B20	B21	B22	B23
6	B24	B25	B26	B27
7	B28	B29	B30	B31

Accessing Data



Step 1: Search in CACHE

IF B2 exists in Cache
- **HIT**

IF B2 NOT found in Cache
- **MISS**
- Proceed to **Step 2**

Cache

0				
1				
2				
3				

Step 2: Access Byte **B2** from Main Memory

Step 3: Copy the entire Block 0 to the Cache

0	B0	B1	**B2**	B3

Main Memory

0	B0	B1	**B2**	B3
1	B4	B5	B6	B7
2	B8	B9	B10	B11
3	B12	B13	B14	B15
4	B16	B17	B18	B19
5	B20	B21	B22	B23
6	B24	B25	B26	B27
7	B28	B29	B30	B31

Two Important Questions

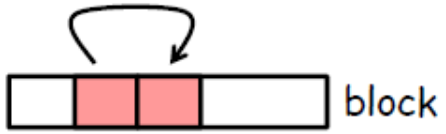
- Why did I copy the entire Block 0 to the cache?
- In which Cache Line will I place Block 0?

Two Important Questions

- Why did I copy the entire Block 0 to the cache?
- In which Cache Line will I place Block 0?

Locality

- “Tendency of a processor to access the same set of memory locations repetitively over a short period of time.”



- Spatial
  - If a Byte is accessed now then the Byte next to it is likely be accessed next
  - The number of Bytes in a block affects spatial locality

- Temporal
  - If a Byte is referenced now then the same Byte is likely be referenced again in the future

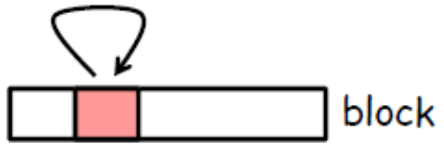


Image Source: Dr Petrucci's Slides - "Cache Memories"

Two Important Questions

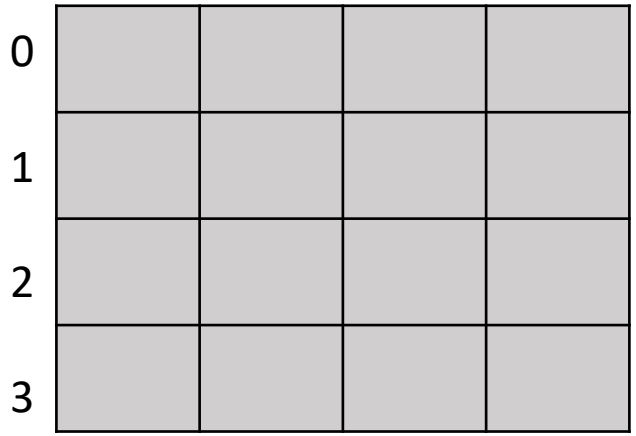
- Why did I copy the entire Block 0 to the cache?

- In which Cache Line will I place Block 0?

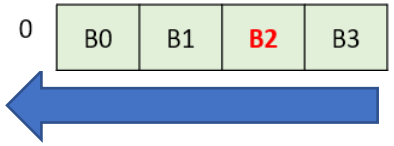
Mapping

- ‘In which *line* of the cache is one *block* of the main memory mapped to?’

Cache



?



Main Memory

0	B0	B1	**B2**	B3
1	B4	B5	B6	B7
2	B8	B9	B10	B11
3	B12	B13	B14	B15
4	B16	B17	B18	B19
5	B20	B21	B22	B23
6	B24	B25	B26	B27
7	B28	B29	B30	B31

Types of Mapping

- Direct Mapping
- Fully Associative Mapping
- Set Associative

Consider a Scenario

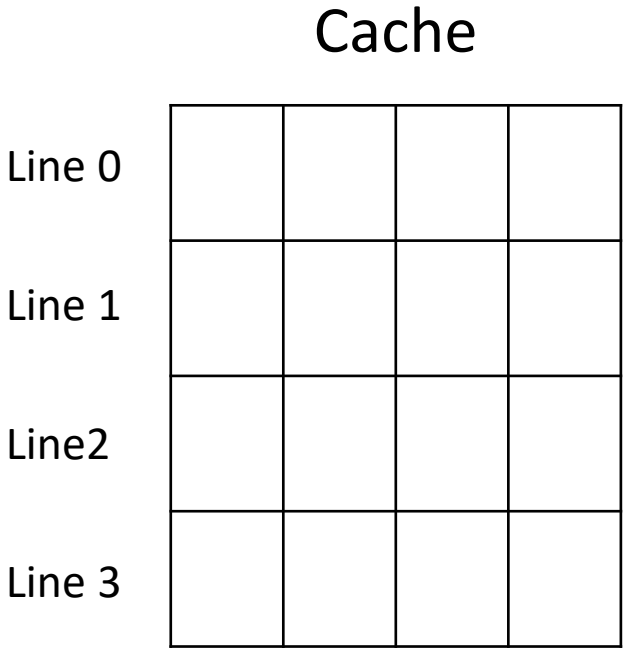
- BYTE addressable
  - Address associated with each Byte
- Main Memory
  - Total number of Bytes = 64
  - Divided into Blocks
    - Block Size = 4 Bytes
  - How many blocks?
    - 64/4 = 16 Blocks

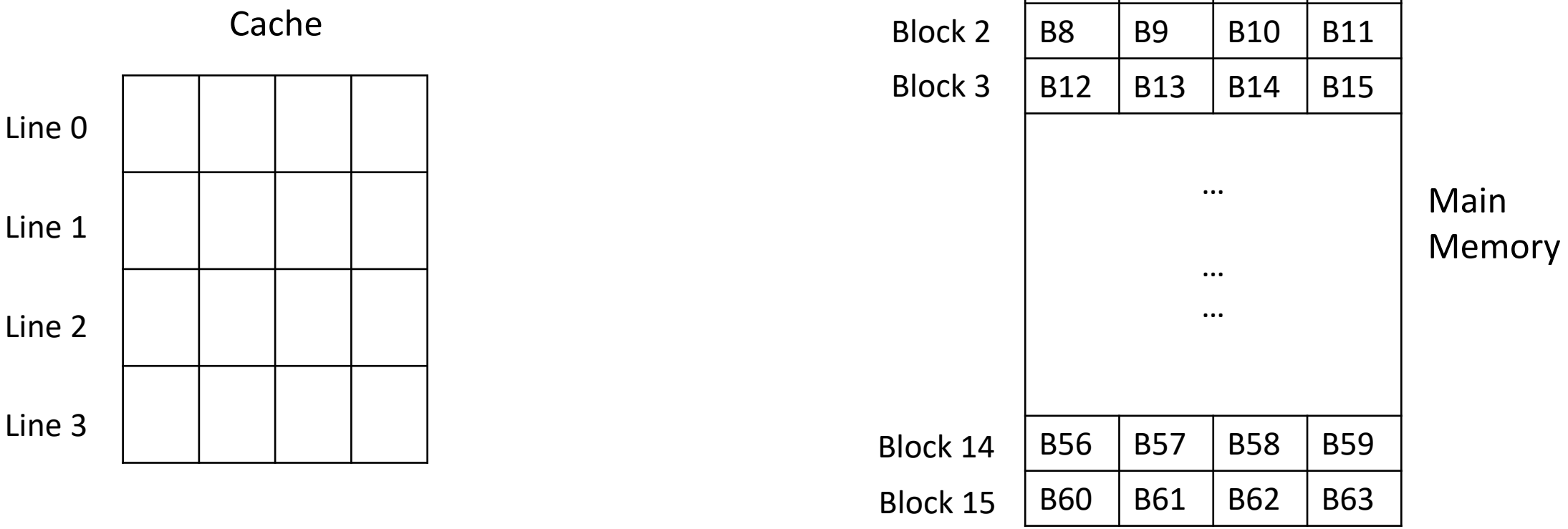
Main Memory

Block 0	B0	B1	B2	B3
Block 1	B4	B5	B6	B7
Block 2	B8	B9	B10	B11
Block 3	B12	B13	B14	B15
	…			
	…			
	…			
Block 14	B56	B57	B58	B59
Block 15	B60	B61	B62	B63

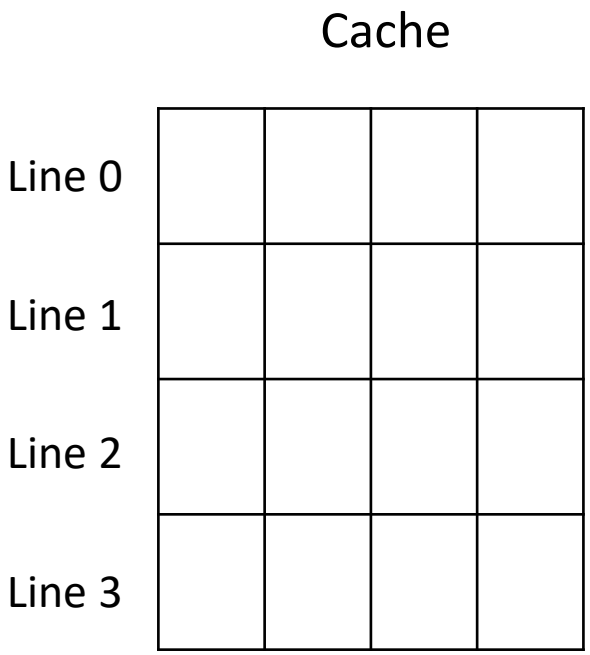
Consider a Scenario

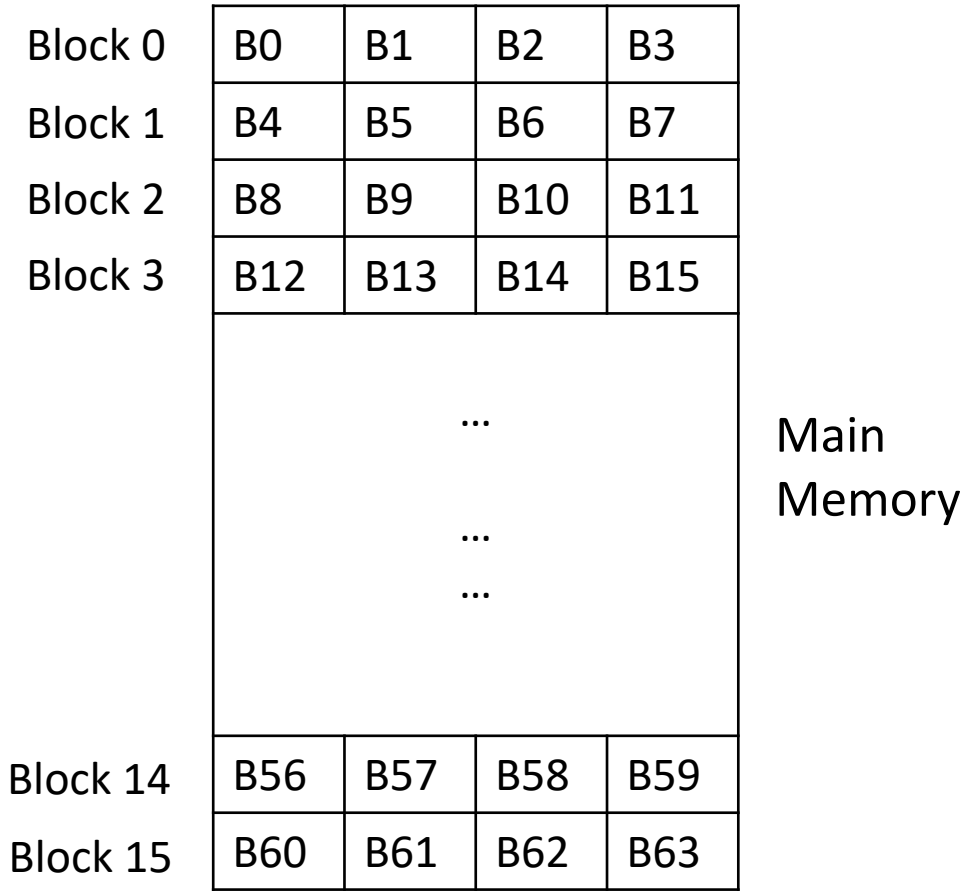
- Byte addressable
  - Address associated with each Byte
- Cache
  - Total number of Bytes = 16
  - Divided into Sets
  - 1 Set = 1 Line
    - Line Size = 4 Bytes
  - How many Lines?
    - 16/4 = 4 Lines



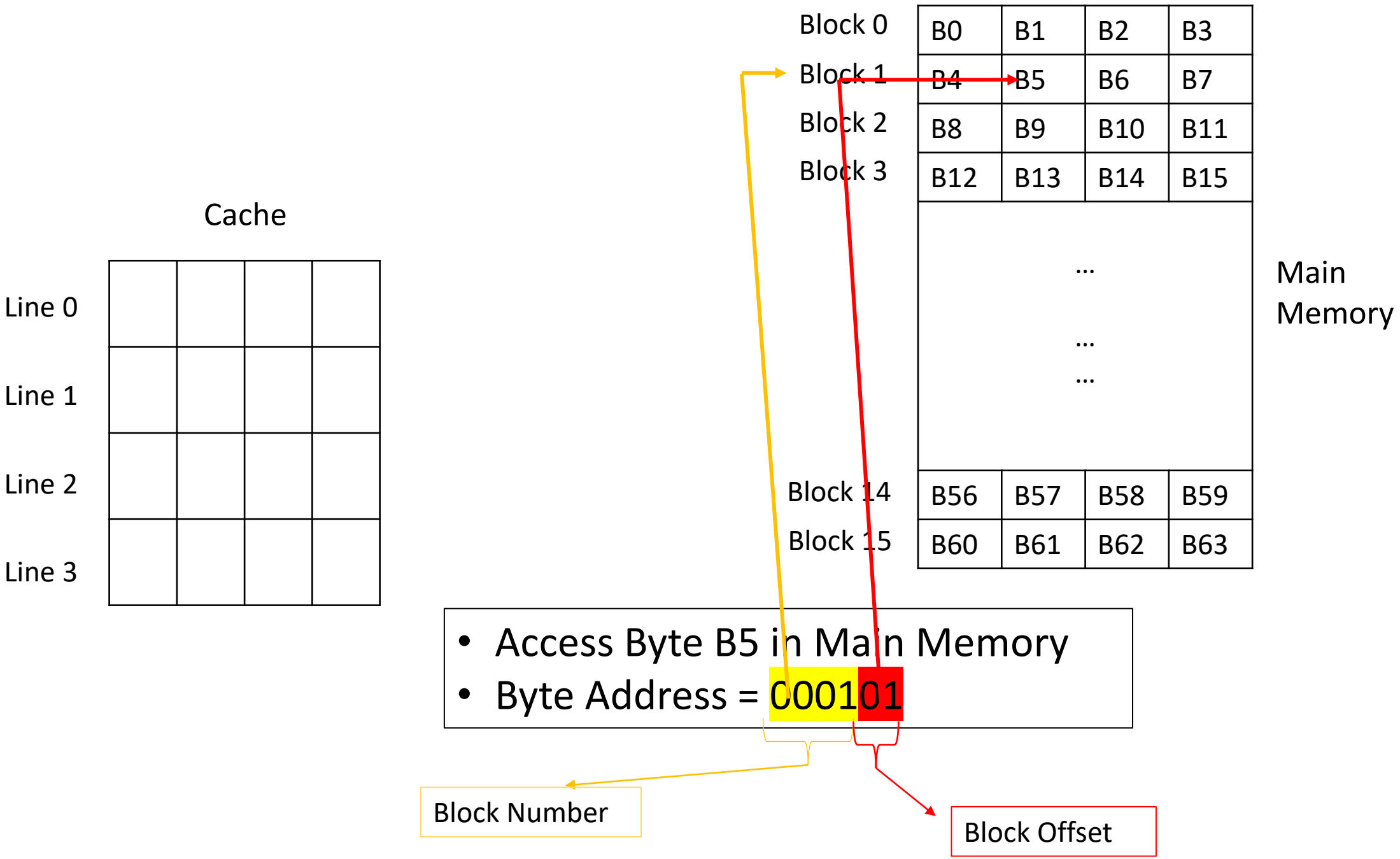


Byte Addressable = Each Byte in Main Memory is identified by an address





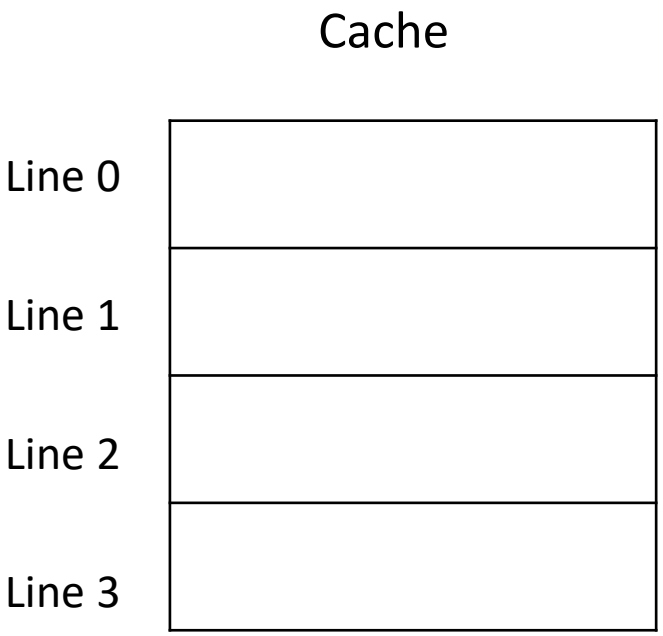
- Number of Bytes in Main Memory = 64 = 2^6
- How many addresses?
  - 64
- How many bits per address?
  - 6-bit address

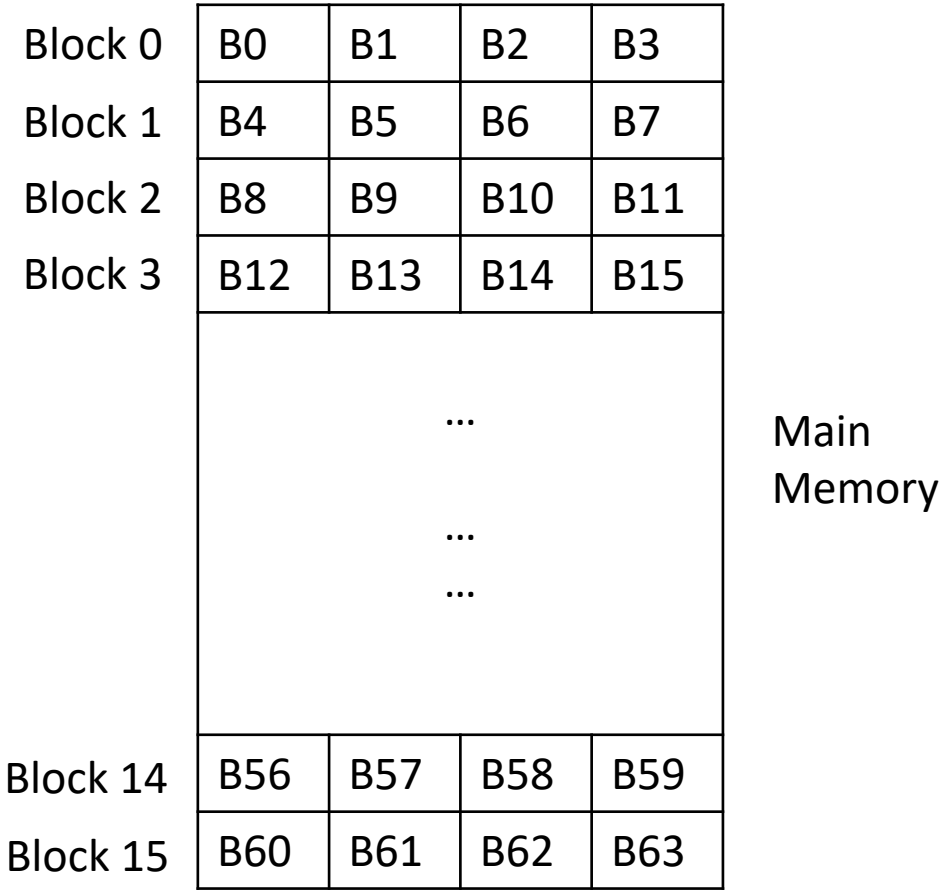

Cache
Line 0
Line 1
Line 2
Line 3
Block 0
Block 1
Block 2
Block 3
B0
B1
B2
B3
B4
B5
B6
B7
B8
B9
B10
B11
B12
B13
B14
B15
...
...
...
Main Memory
Block 14
Block 15
B56
B57
B58
B59
B60
B61
B62
B63
• Access Byte B5 in Main Memory
• Byte Address = 000101
Block Number
Block Offset

Direct Mapping

Direct Mapping

1 Set = 1 Line





- Mapped in Round Robin manner
- Line Number = K mod n
  - K = Block Number
  - n = Number of lines

Direct Mapping

1 Set = 1 Line

Cache

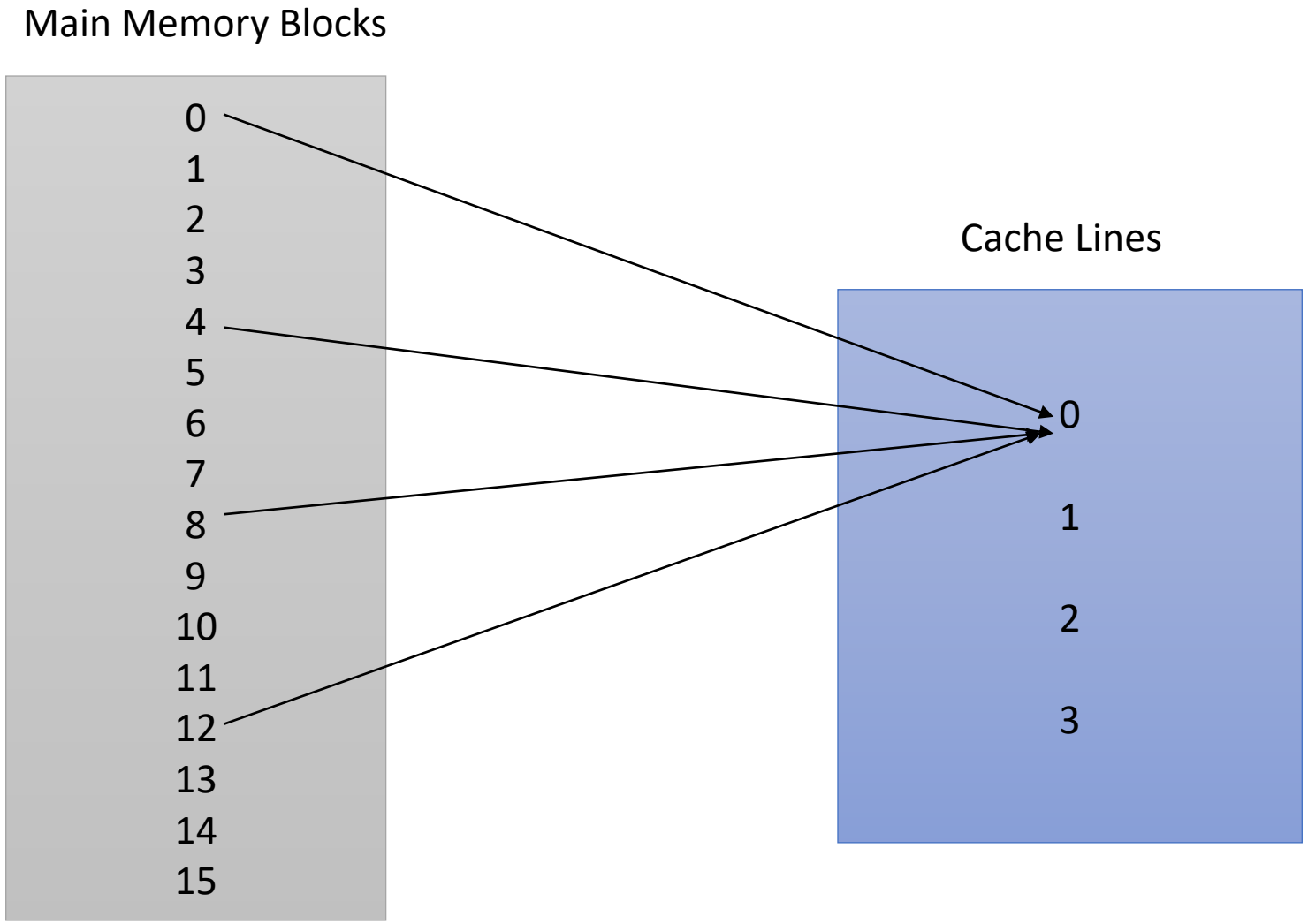
Line 0	Block 0/4/8/12
Line 1	Block 1/5/9/13
Line 2	Block 2/6/10/14
Line 3	Block 3/7/11/15

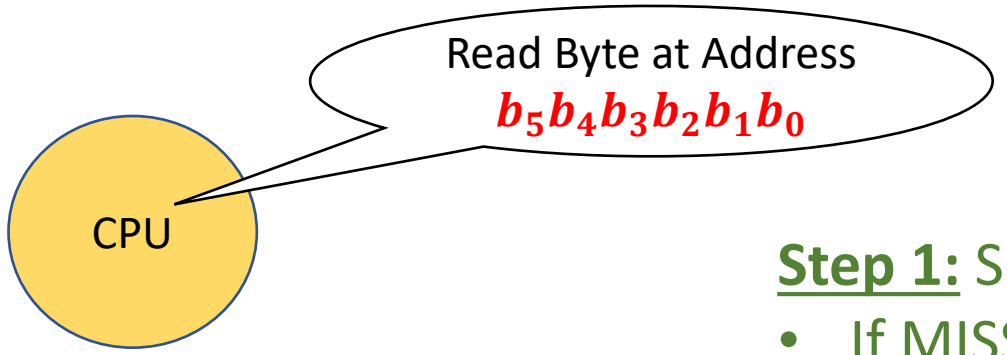
Block 0	B0	B1	B2	B3
Block 1	B4	B5	B6	B7
Block 2	B8	B9	B10	B11
Block 3	B12	B13	B14	B15
	...			
	...			
	...			
Block 14	B56	B57	B58	B59
Block 15	B60	B61	B62	B63

Main Memory

- Mapped in Round Robin manner
- Line Number = K mod n
  - K = Block Number
  - n = Number of lines

Direct Mapping – Many to One Mapping

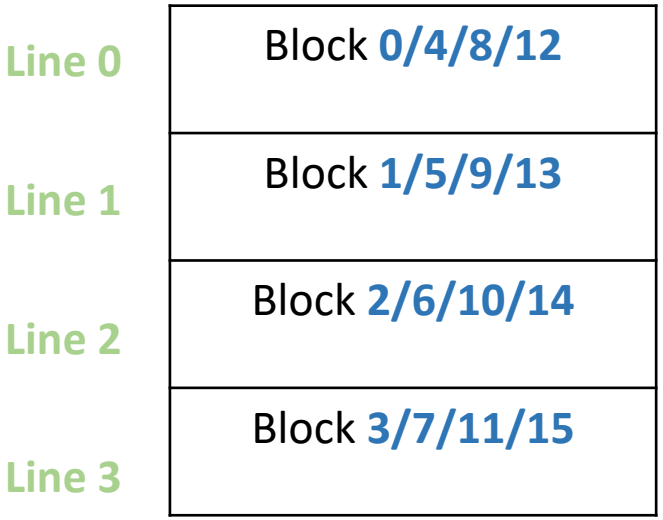




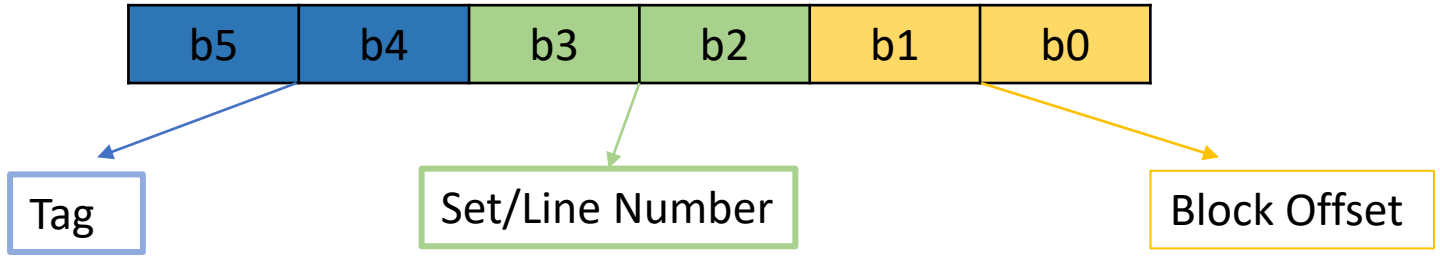
Step 1: Search in Cache

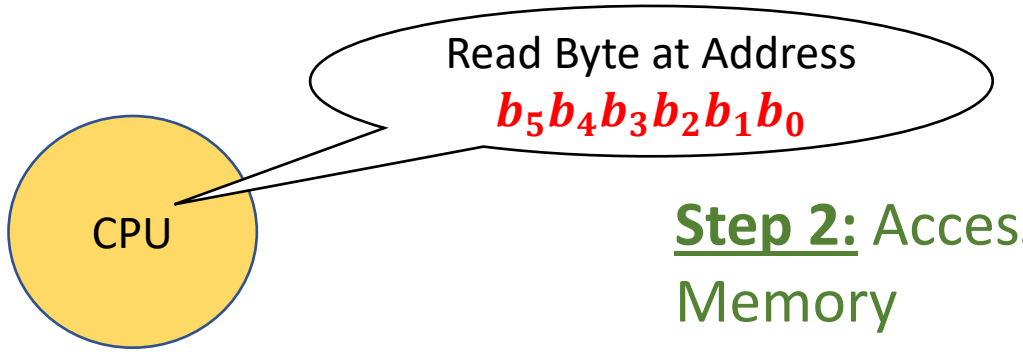
- If MISS, go to **Step 2**

Cache



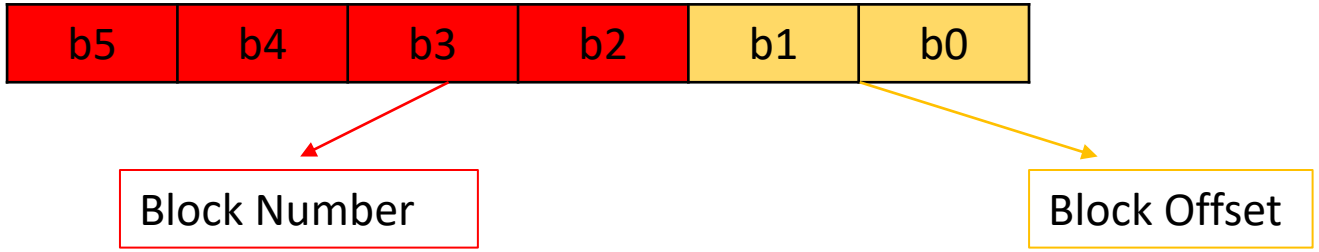
Byte address





Step 2: Access From Main Memory

Byte address

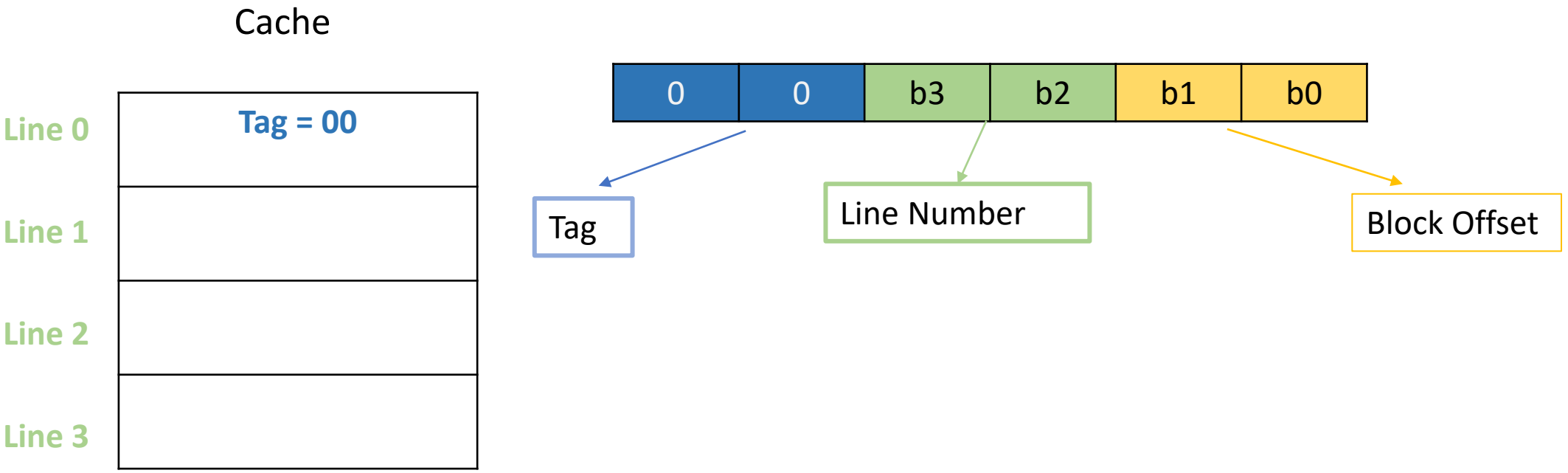


Block 0	B0	B1	B2	B3
Block 1	B4	B5	B6	B7
Block 2	B8	B9	B10	B11
Block 3	B12	B13	B14	B15
	…			
	…			
	…			
Block 14	B56	B57	B58	B59
Block 15	B60	B61	B62	B63

Main Memory

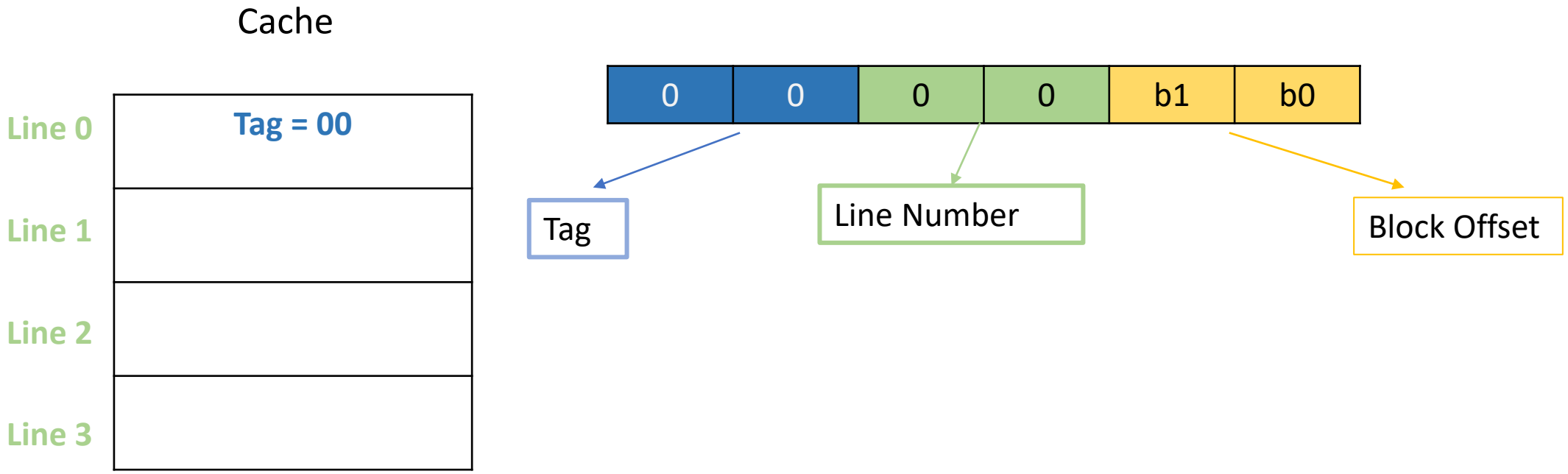
Direct Mapping

- Suppose Line 0 of the cache has Tag ’00’
  - What are the addresses of the Bytes present in line 0 of the cache?



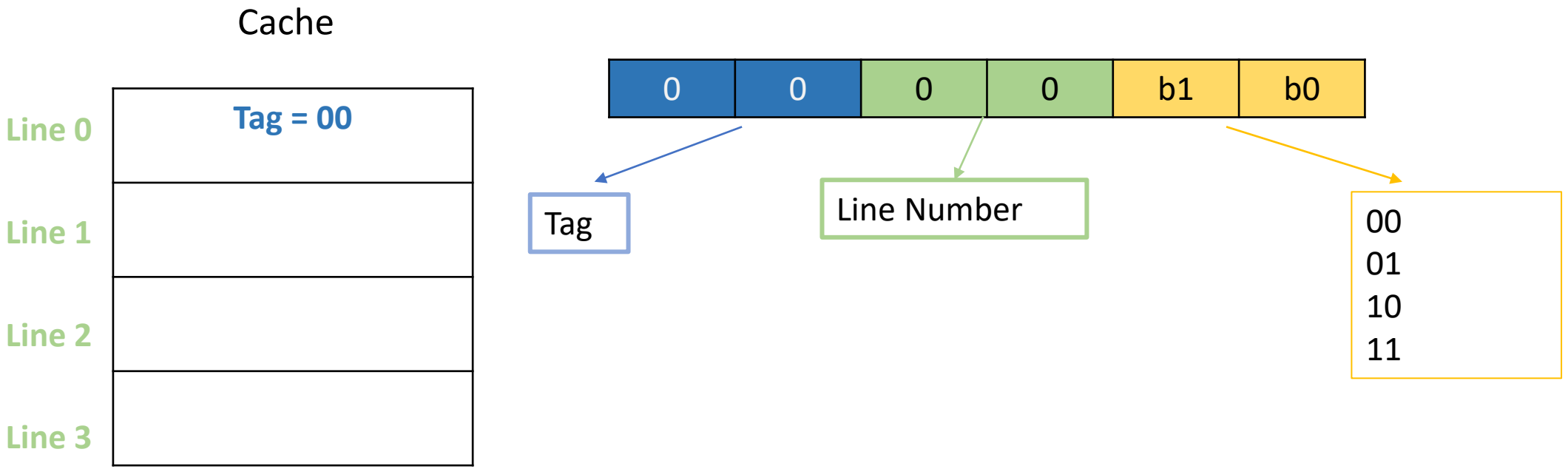
Direct Mapping

- Suppose Line 0 of the cache has Tag ’00’
  - What are the addresses of the Bytes present in line 0 of the cache?



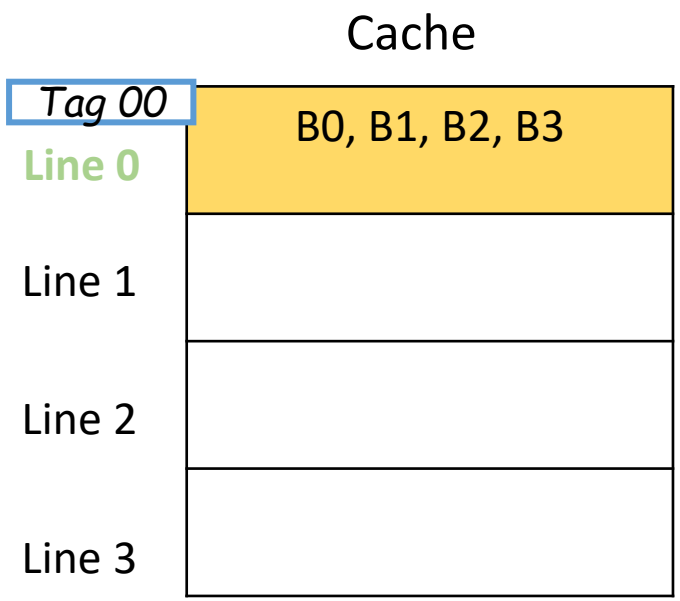
Direct Mapping

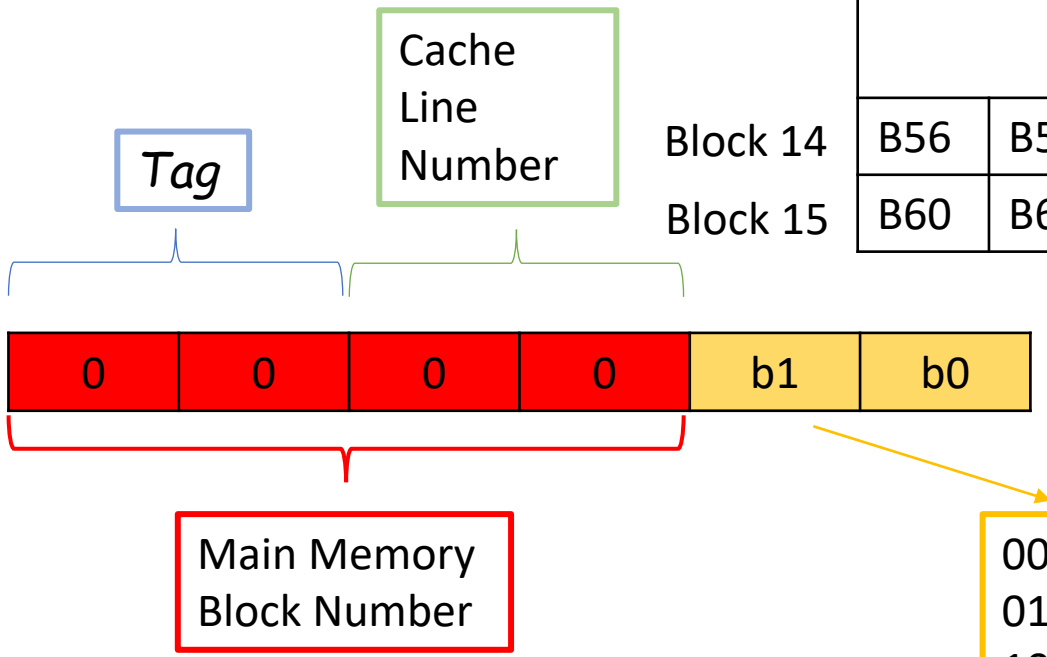
- Suppose Line 0 of the cache has Tag ’00’
  - What are the addresses of the Bytes present in line 0 of the cache?



Direct Mapping

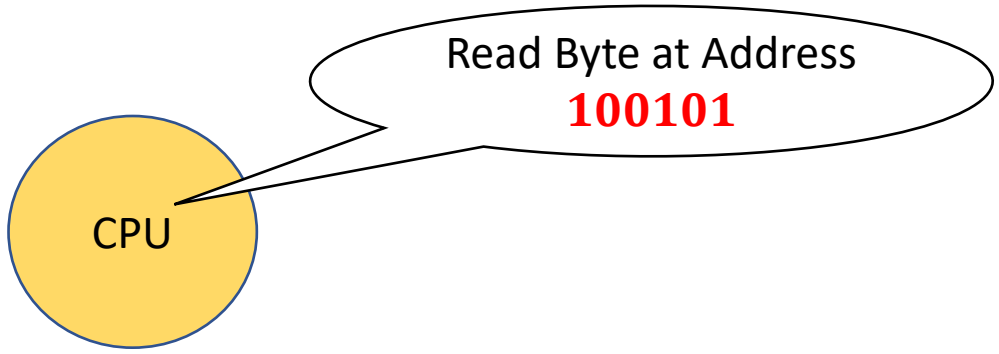
- Suppose Line 0 of the cache has Tag ’00’
  - What are the addresses of the Bytes present in line 0 of the cache?



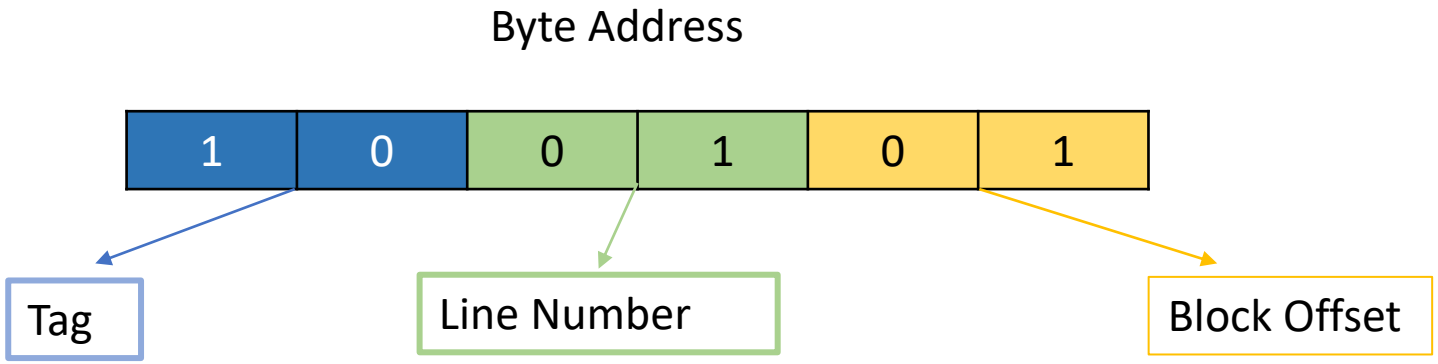


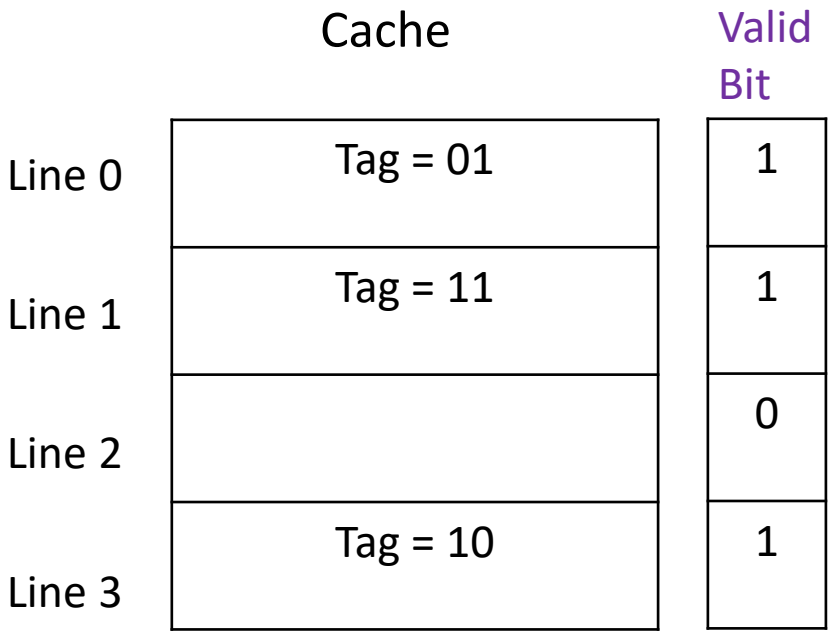
Block 0	B0	B1	B2	B3
Block 1	B4	B5	B6	B7
Block 2	B8	B9	B10	B11
Block 3	B12	B13	B14	B15
	…			
	…			
	…			
Block 14	B56	B57	B58	B59
Block 15	B60	B61	B62	B63

Main Memory



Sequence of Actions



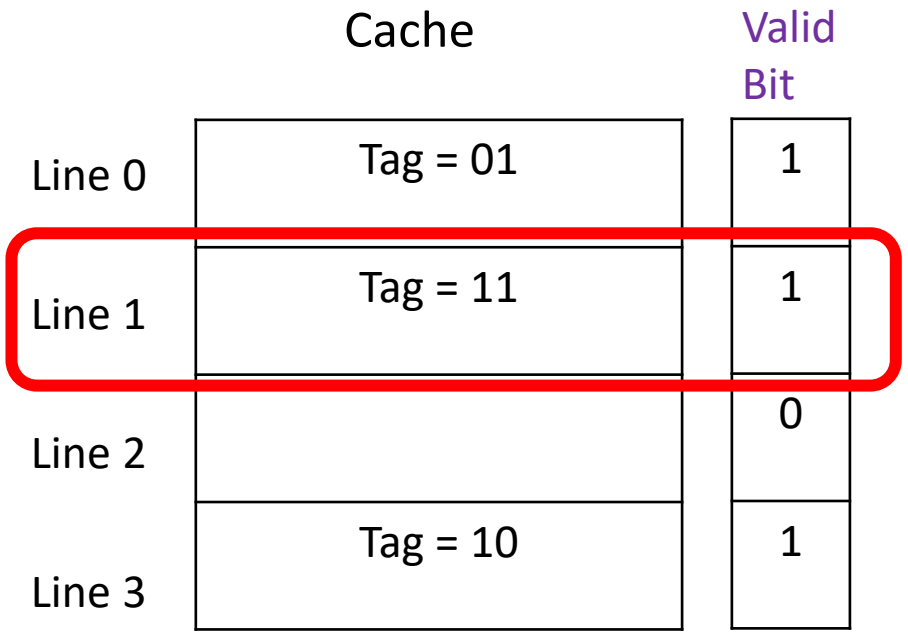


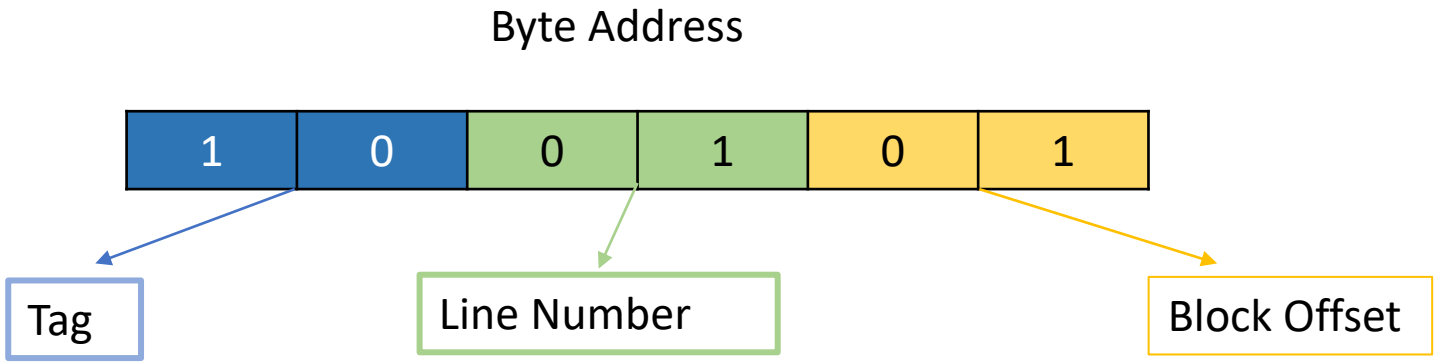
Step 1: Go to **Line Number** 01

Step 2: Check **Valid Bit.** If Valid Bit = 0, then it's a **MISS**. If Valid Bit = 1, go to Step 3

Step 3: If Tag matches, then it's **HIT**, or else **MISS**

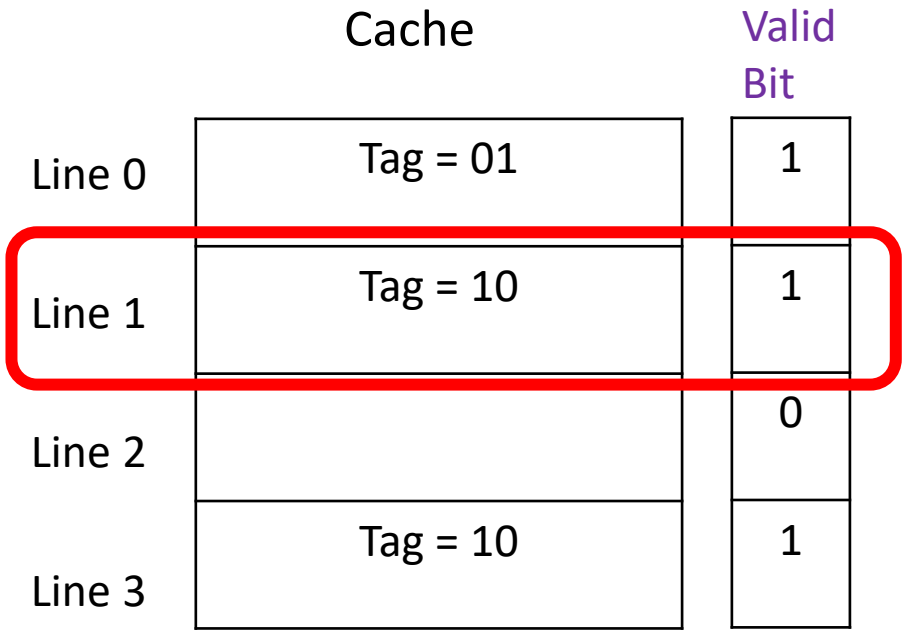
Sequence of Actions

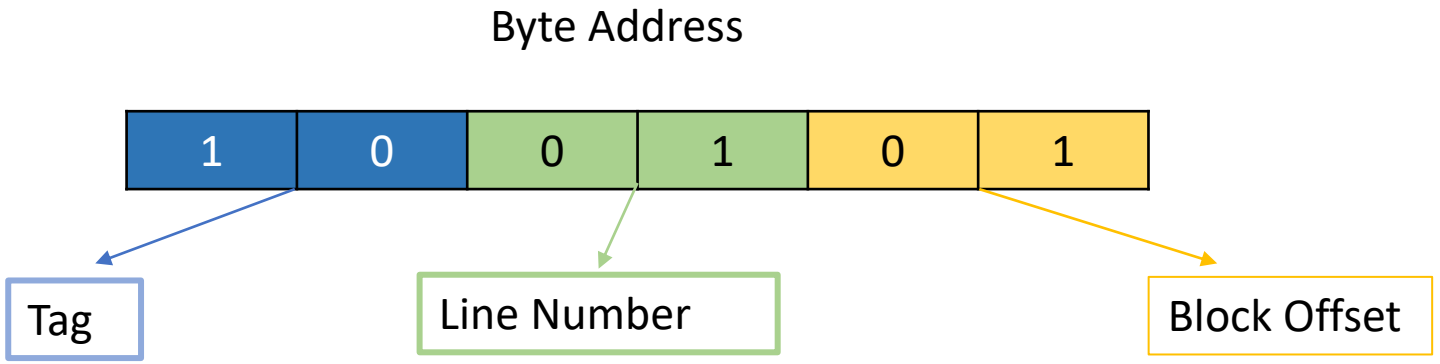




This is a MISS!!

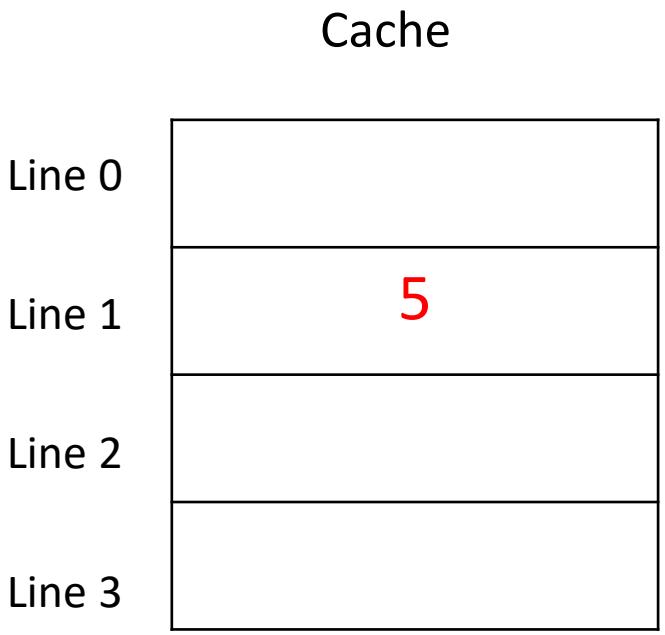
Sequence of Actions





This is a HIT!!

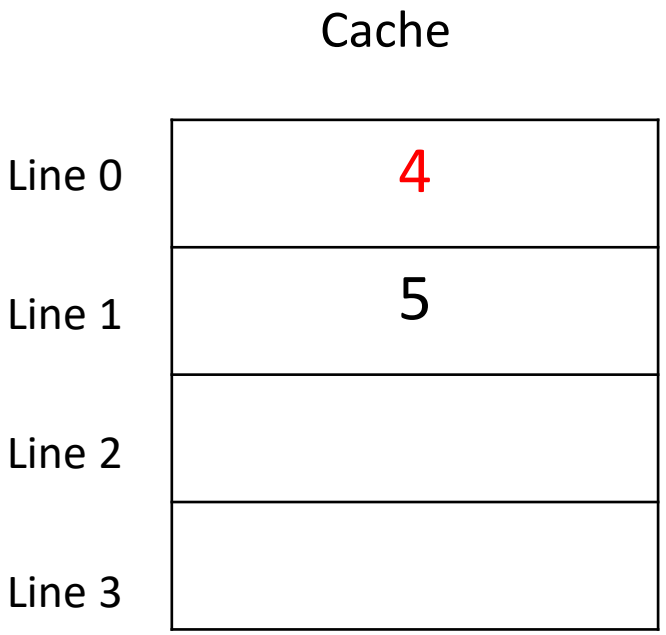
Disadvantages of Direct Mapping



Sequence of Block Numbers requested by CPU

5, 4, 8 , 12, 9, 13

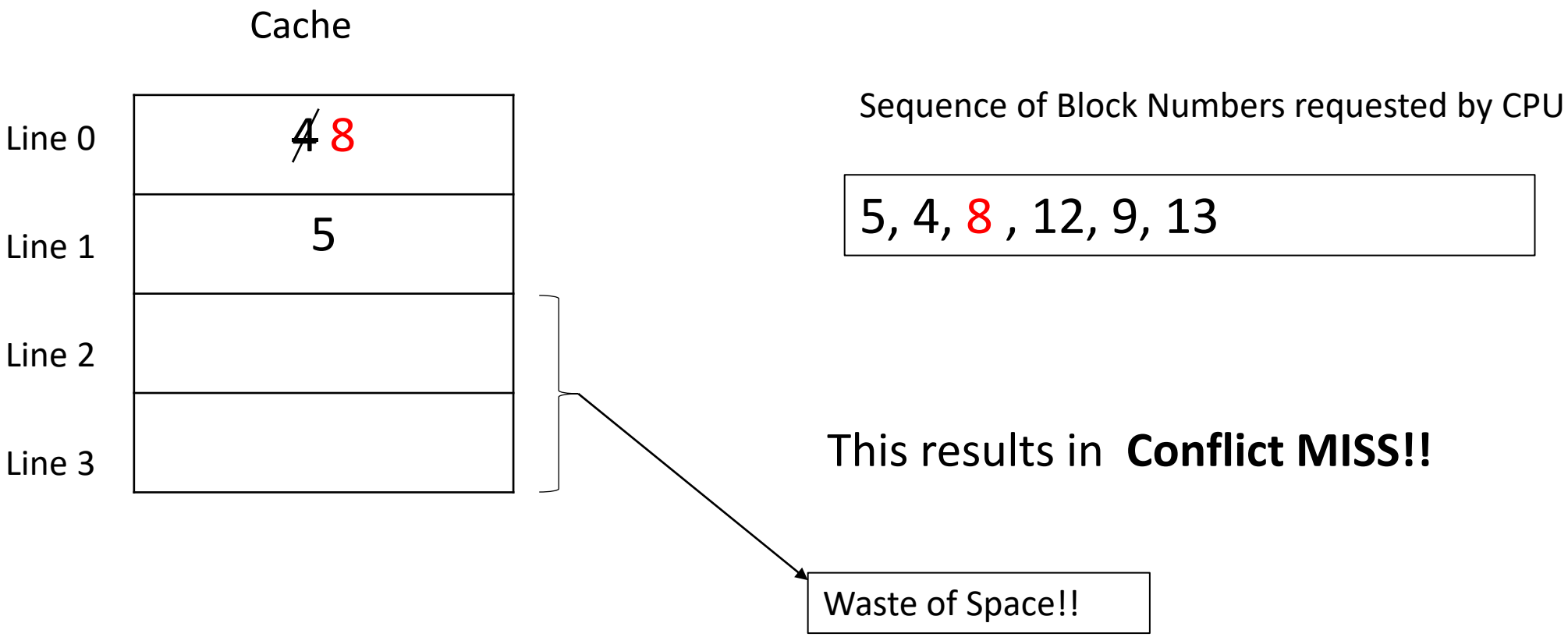
Disadvantages of Direct Mapping



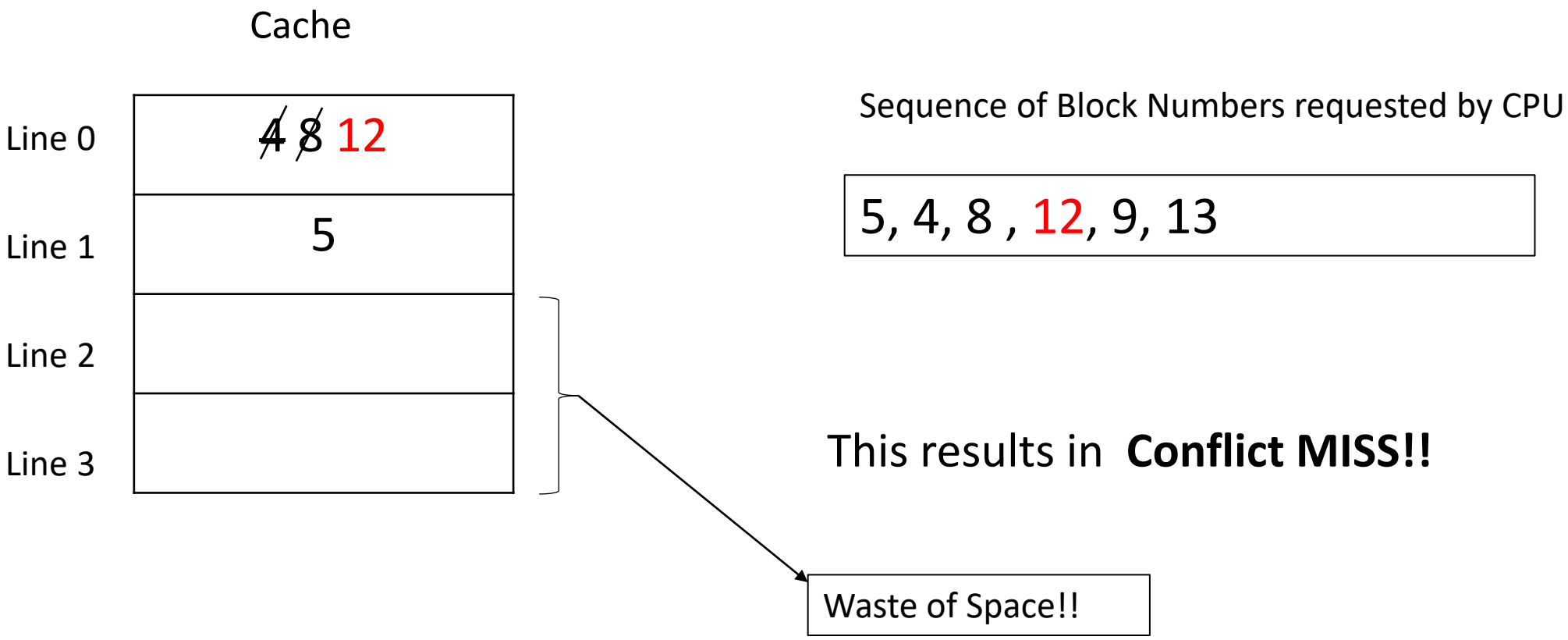
Sequence of Block Numbers requested by CPU

5, 4, 8 , 12, 9, 13

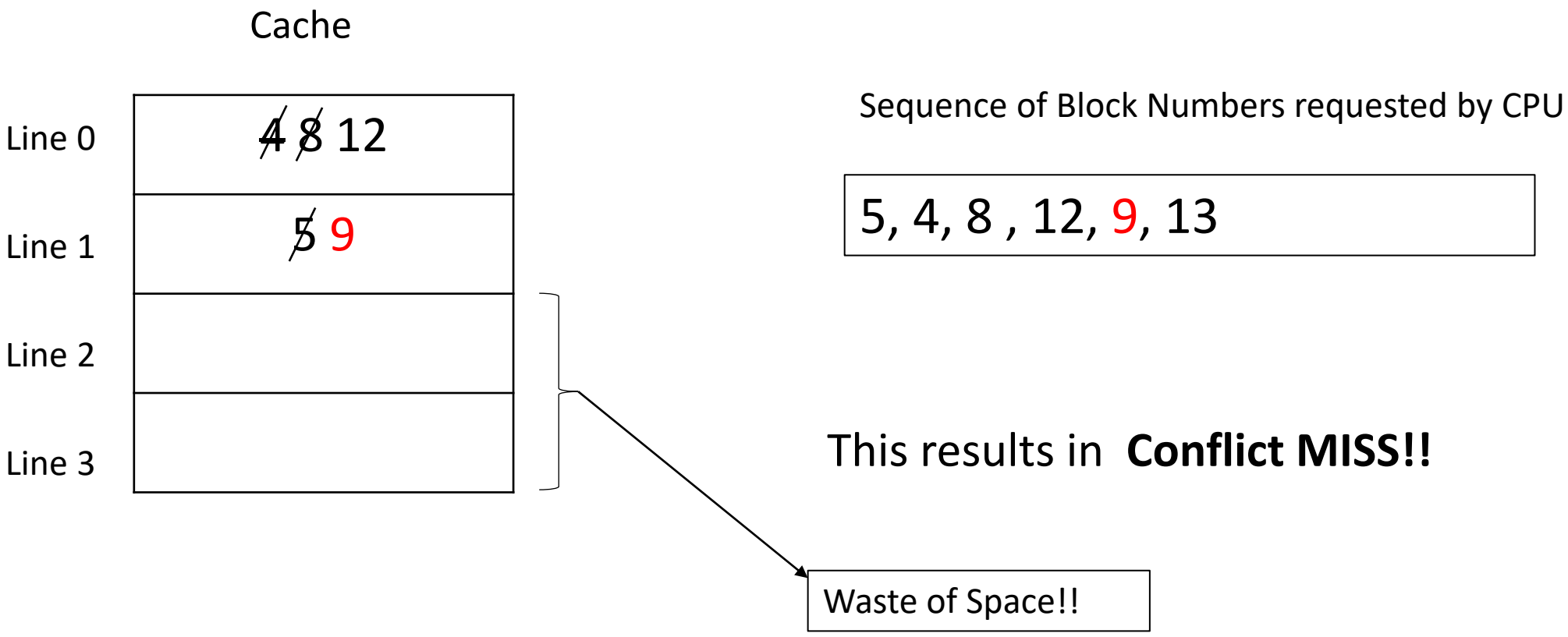
Disadvantages of Direct Mapping



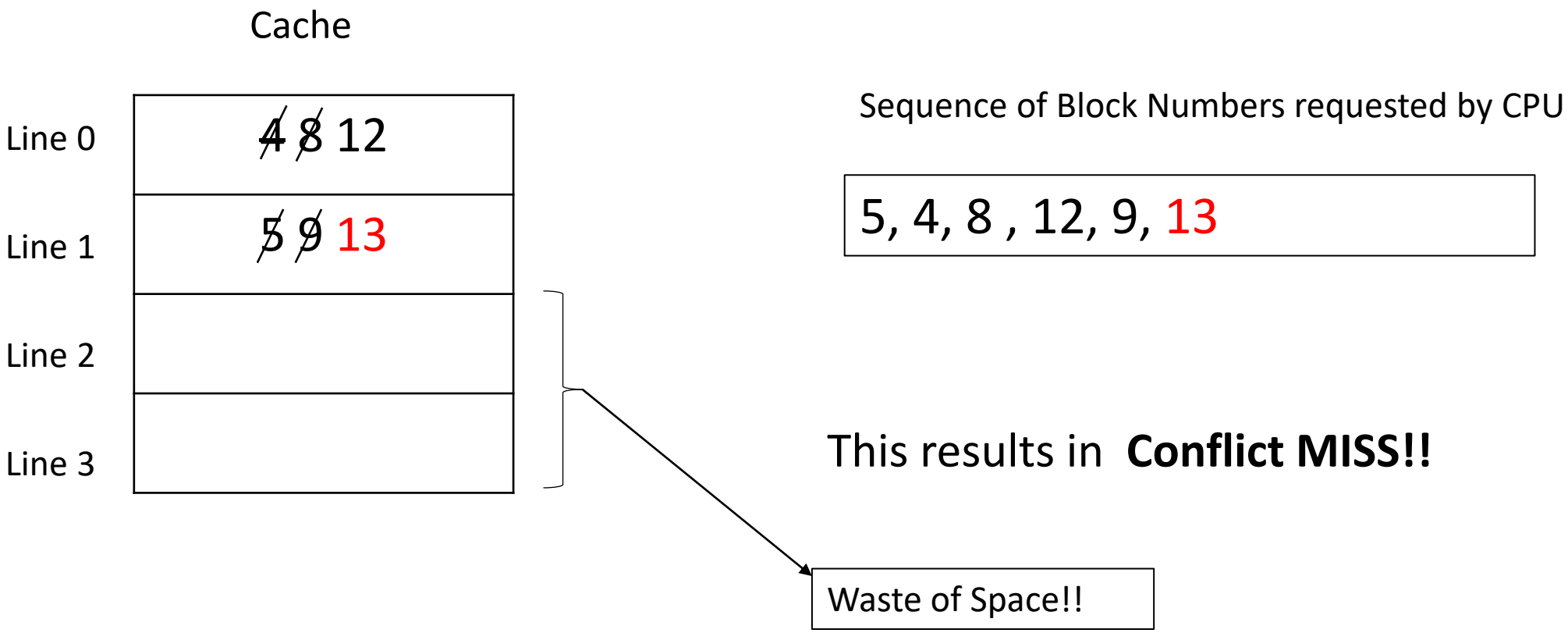
Disadvantages of Direct Mapping



Disadvantages of Direct Mapping



Disadvantages of Direct Mapping



Solutions

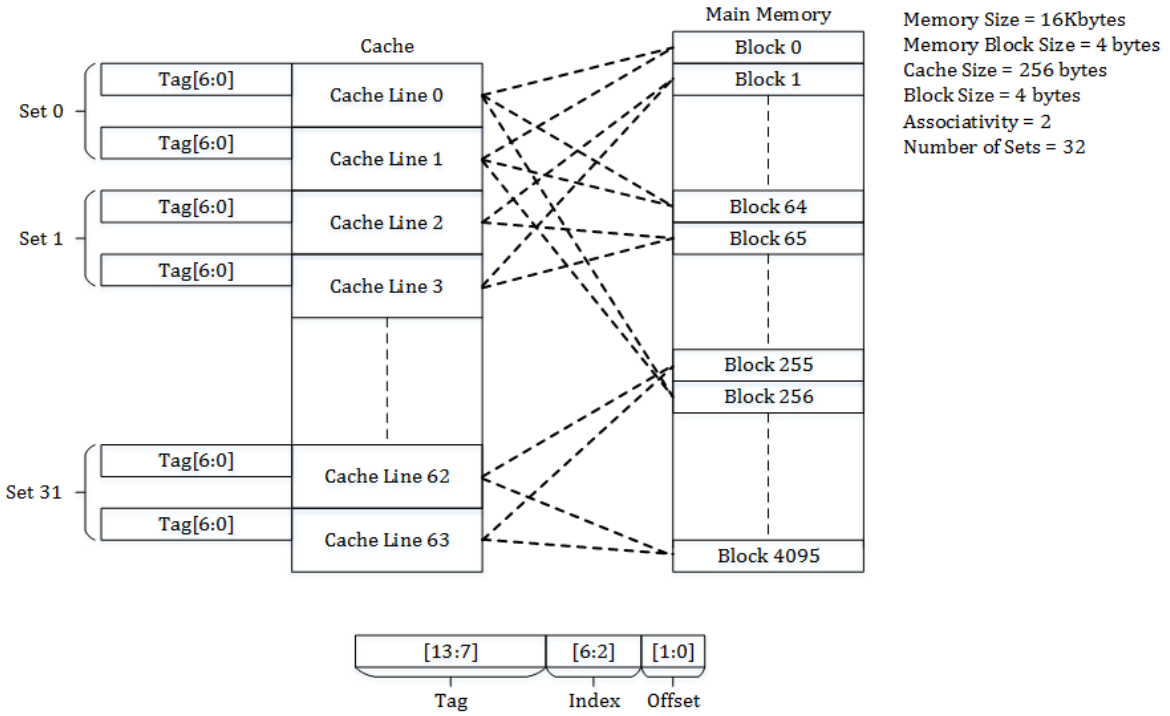
- Fully Associative Mapping
  - A Main Memory Block can be mapped to any Cache line.
  - Advantages: Better Cache Hit Rate

  - **Disadvantages**
    - Slow because the valid bit and tag of every cache line has to be compared.
    - Expensive due to the high cost of associative-comparison hardware.

Solutions

- Set Associative Mapping
  - Cache lines grouped into sets
  - A main memory block is mapped to a set
    - Associative Mapping within a set
  - Tradeoff between Direct Mapping and Fully Associative Mapping
  - **Disadvantages**
    - Can still suffer from conflict miss.

- More details in next recitation



References

- https://www.youtube.com/watch?v=VePK5TNgQU8
- https://www.youtube.com/watch?v=N_OJn7jdKCc
- https://en.wikipedia.org/wiki/Cache_placement_policies
- Locality