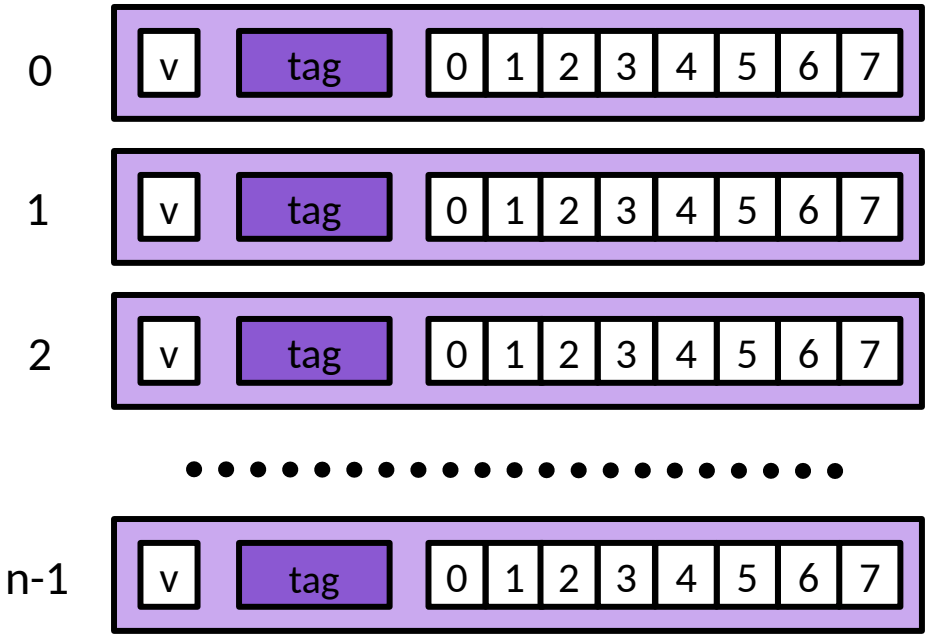
Lecture 11: Caches (cont'd)

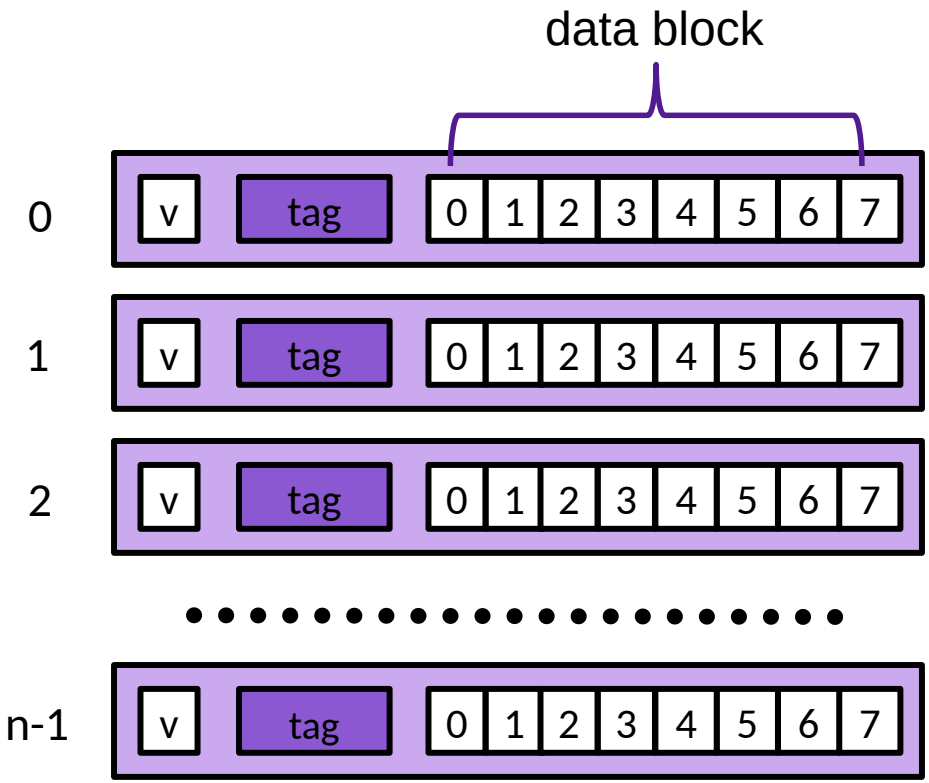
CS 105

Spring 2025

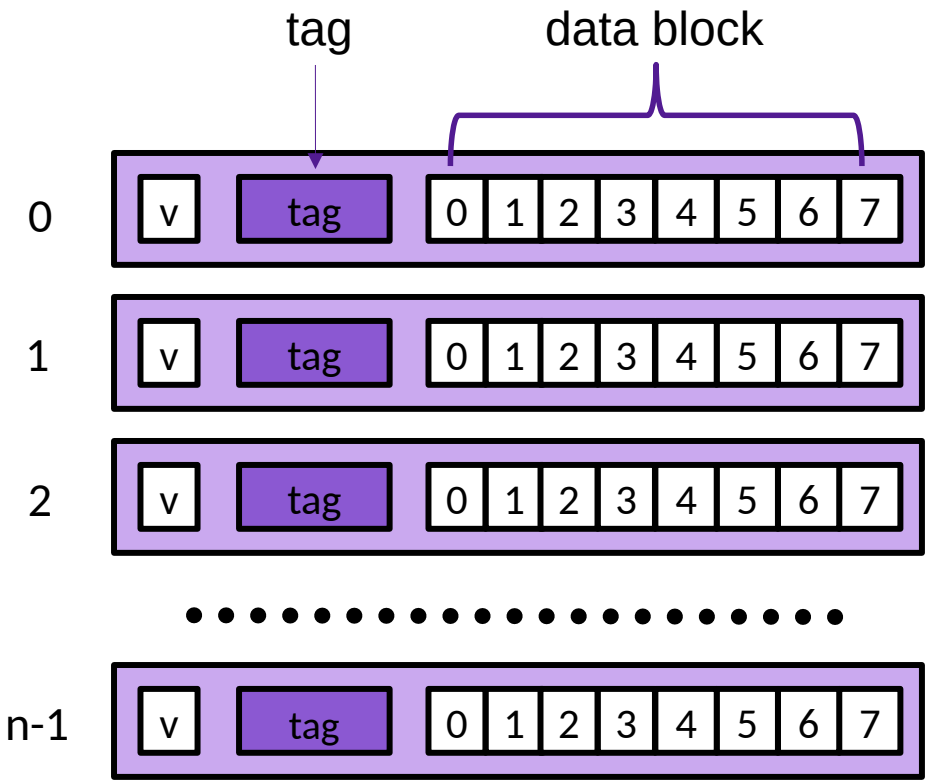
Review: Direct-mapped Cache



Review: Direct-mapped Cache



Review: Direct-mapped Cache



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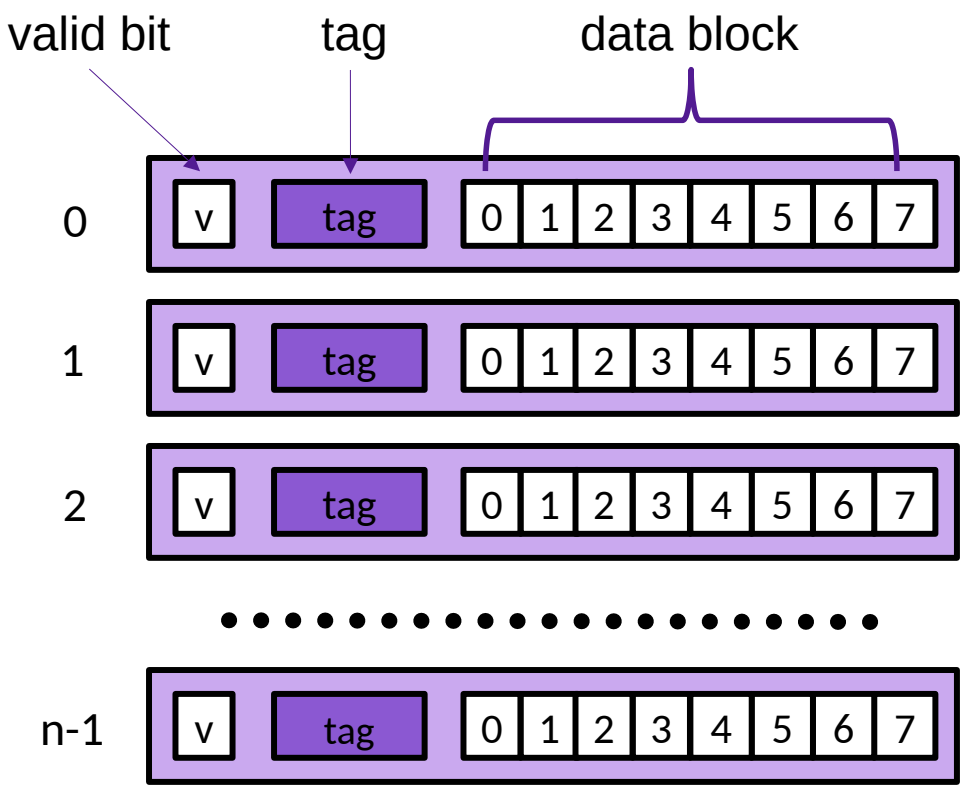
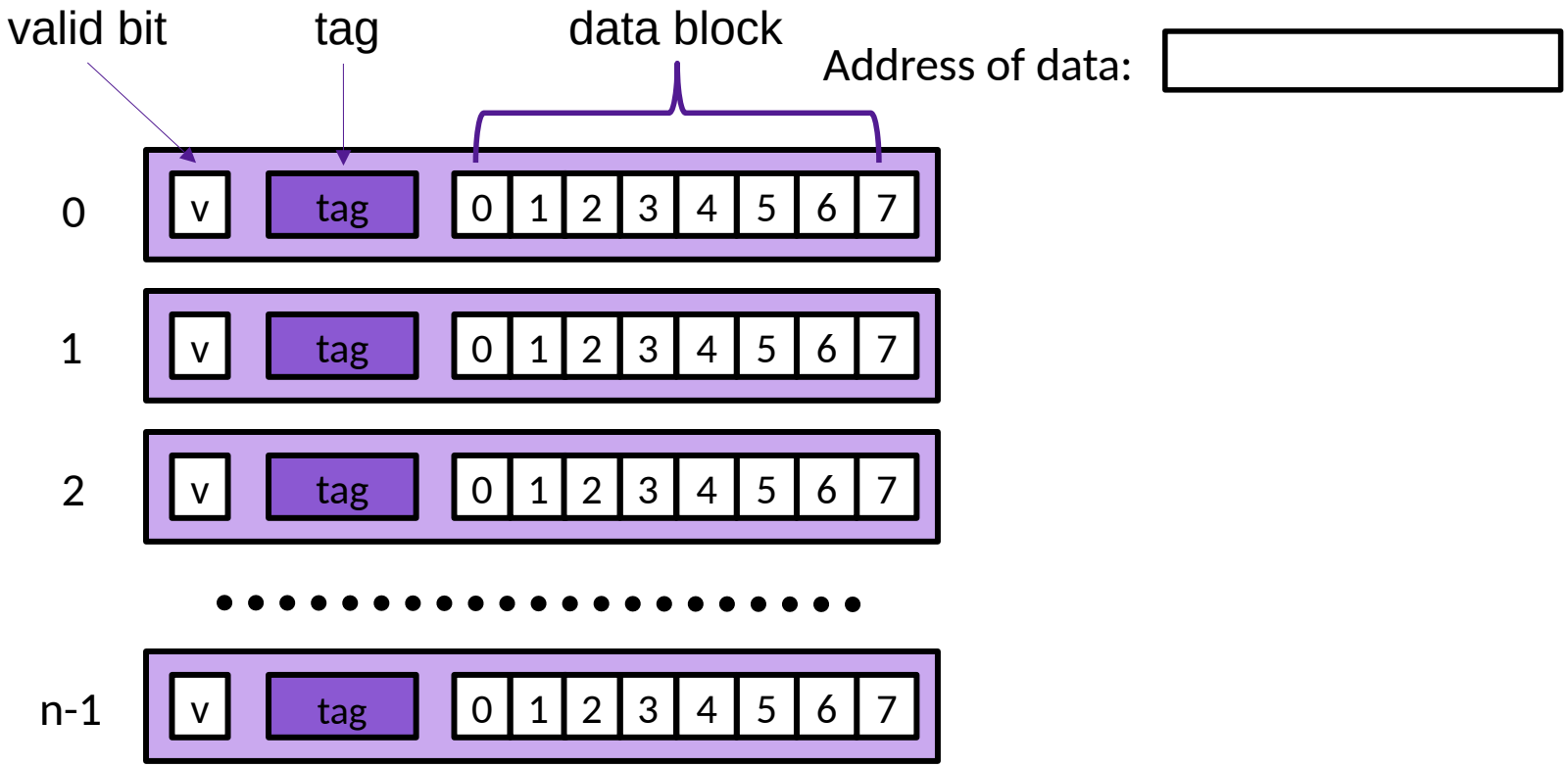


Review: Direct-mapped Cache



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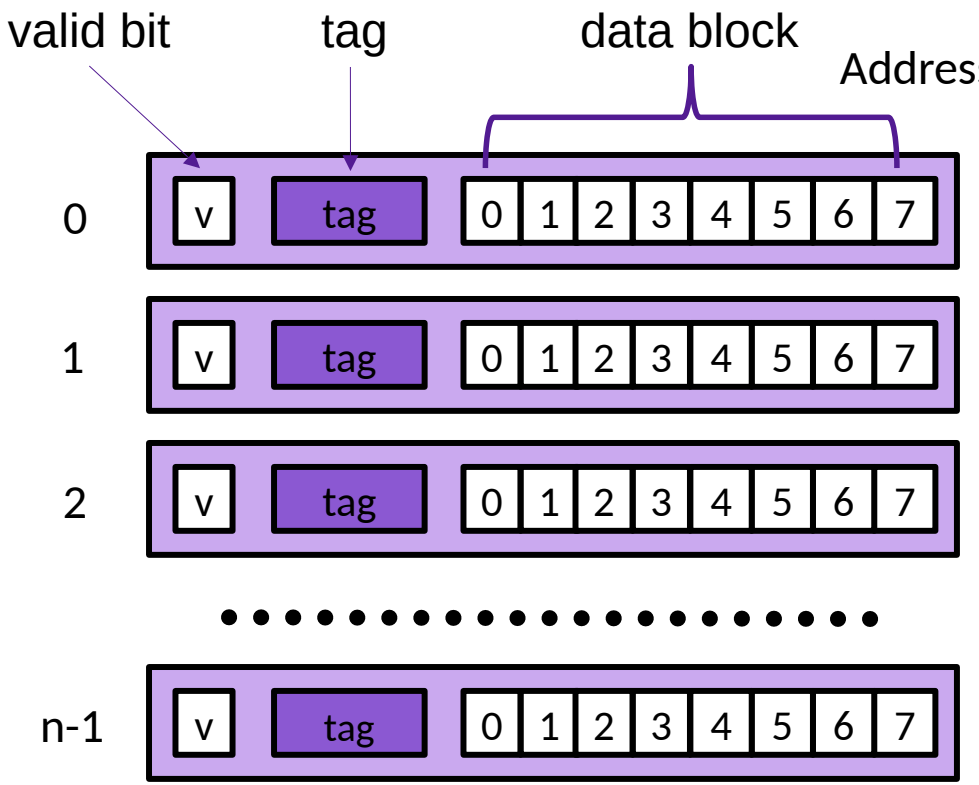
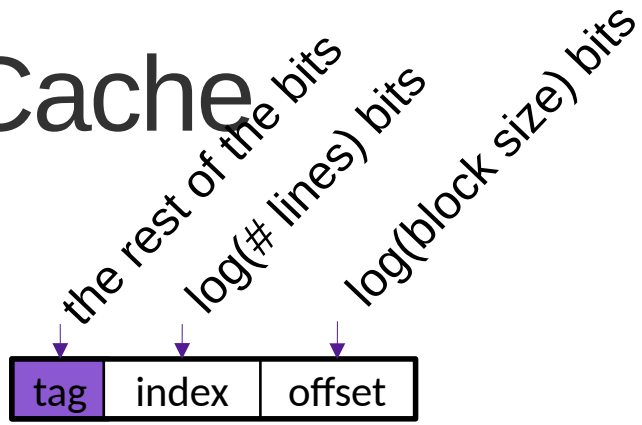
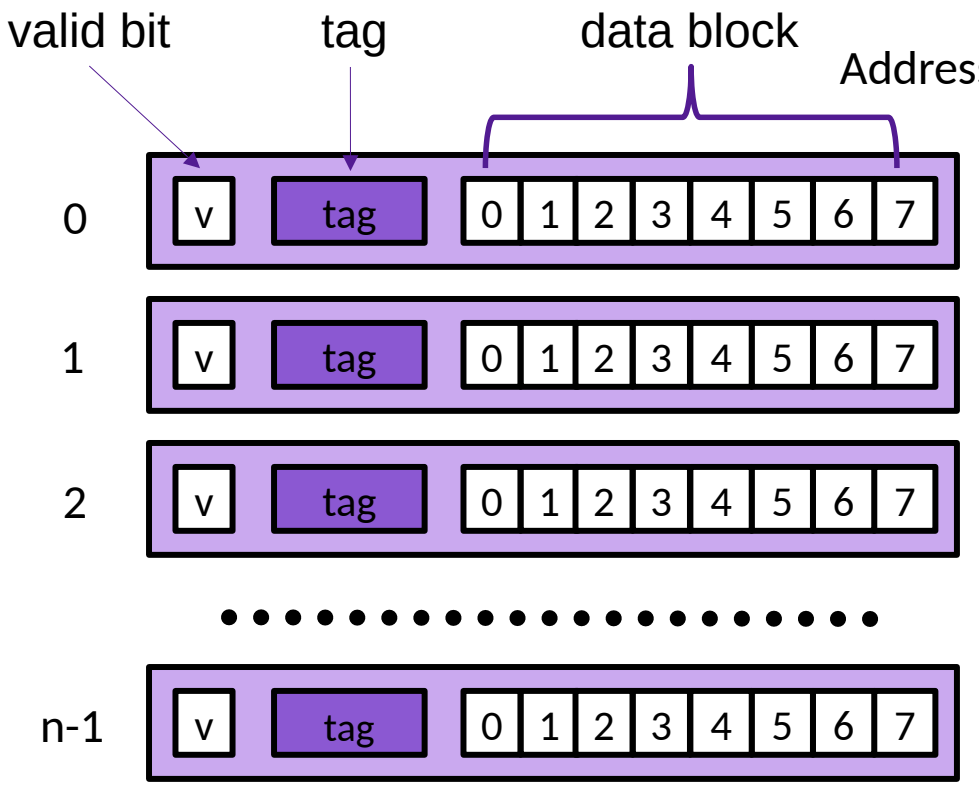
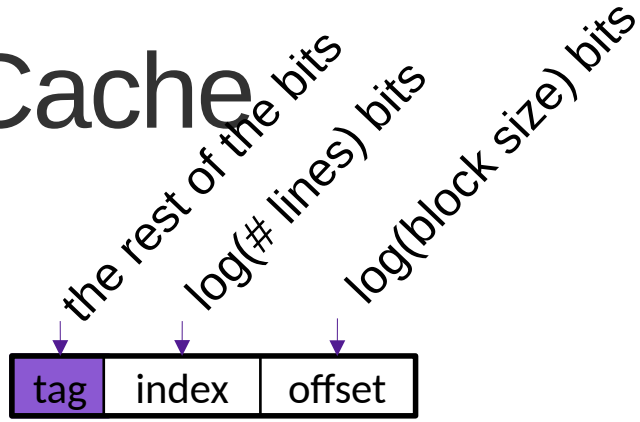




Review: Direct-mapped Cache

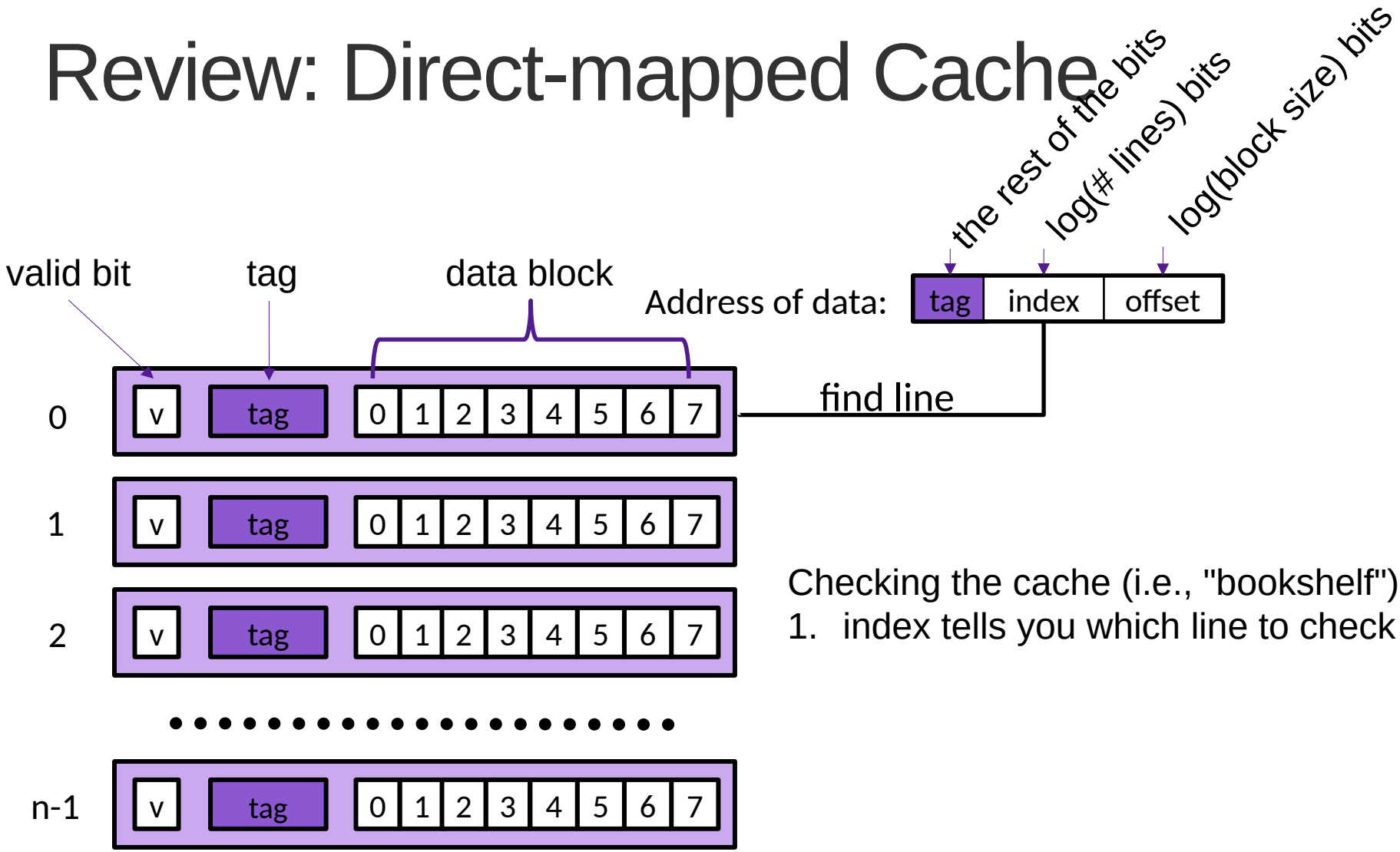


Address of data:



Checking the cache (i.e., "bookshelf"):

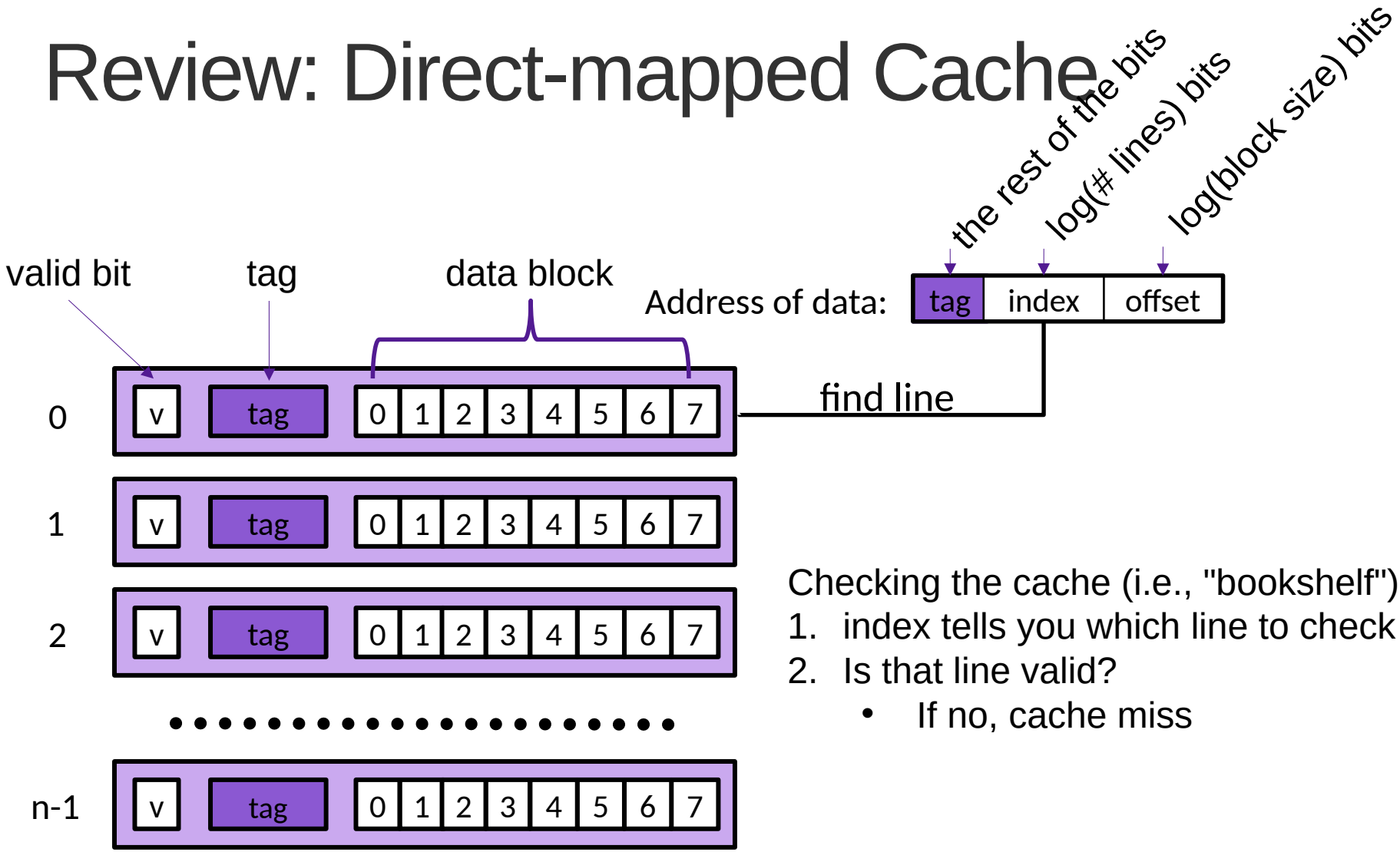
Review: Direct-mapped Cache



Checking the cache (i.e., "bookshelf"):

1. index tells you which line to check

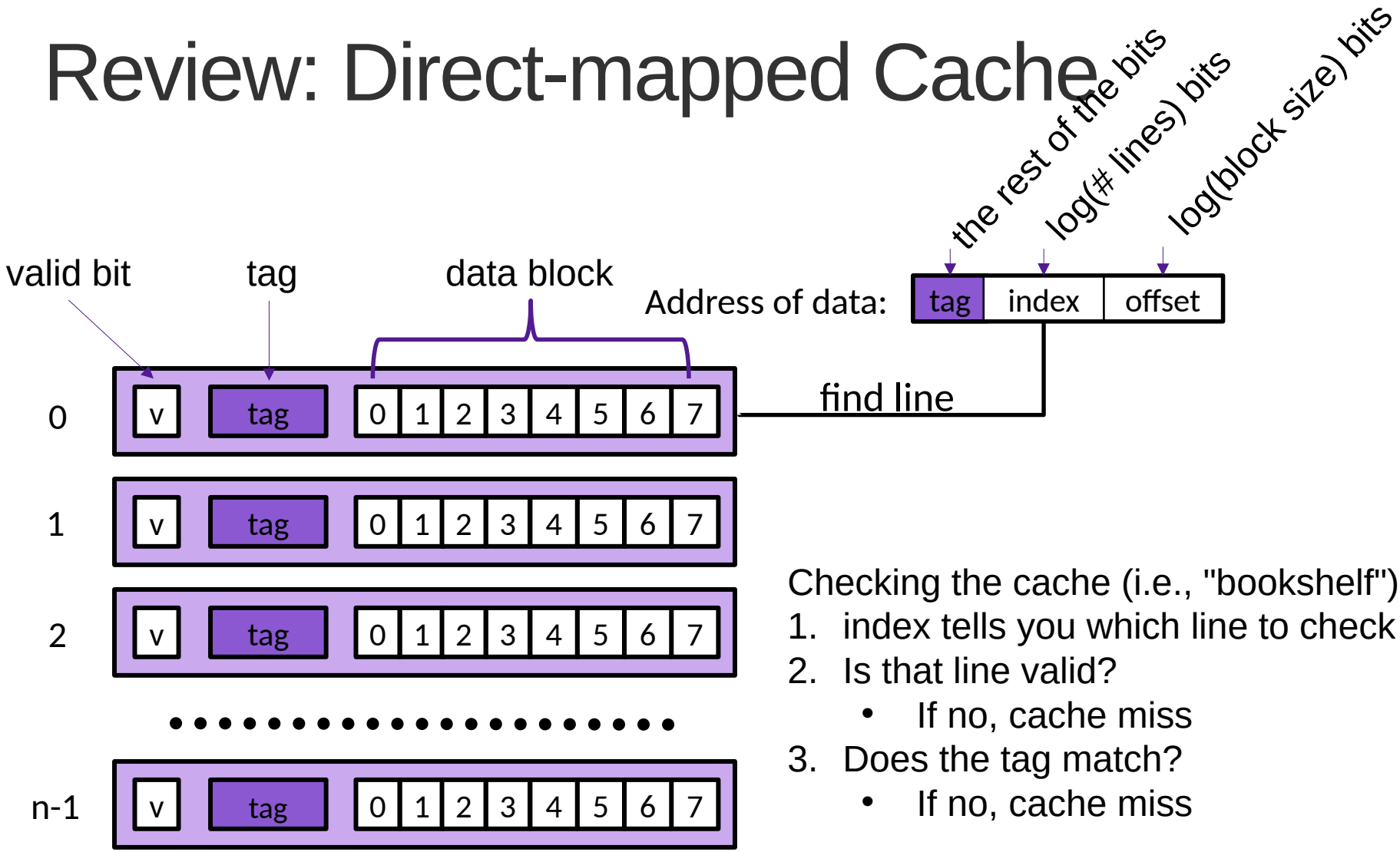
Review: Direct-mapped Cache



Checking the cache (i.e., "bookshelf"):

1. index tells you which line to check
2. Is that line valid?
   - If no, cache miss

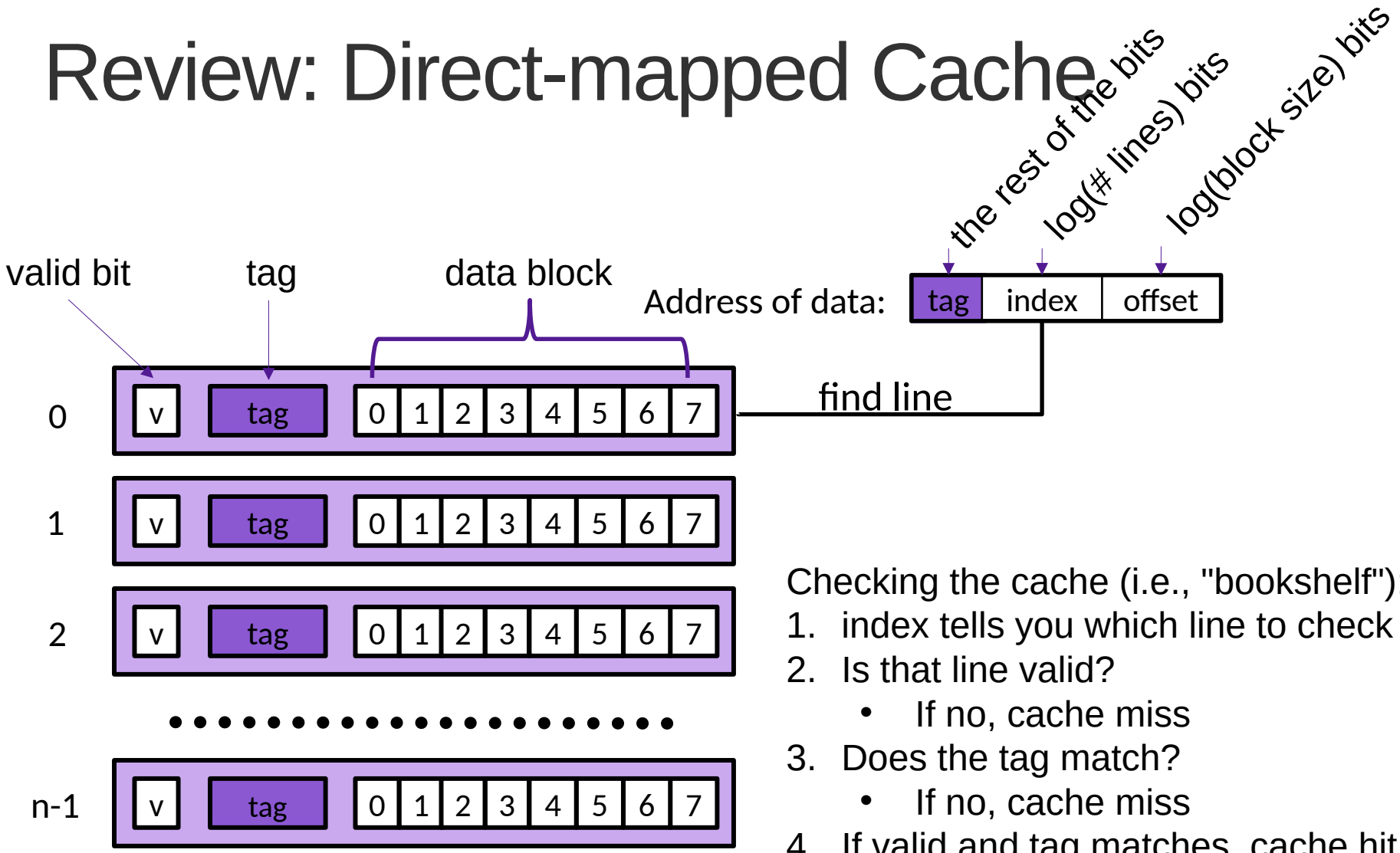
Review: Direct-mapped Cache



Checking the cache (i.e., "bookshelf"):

1. index tells you which line to check
2. Is that line valid?
   - If no, cache miss
3. Does the tag match?
   - If no, cache miss

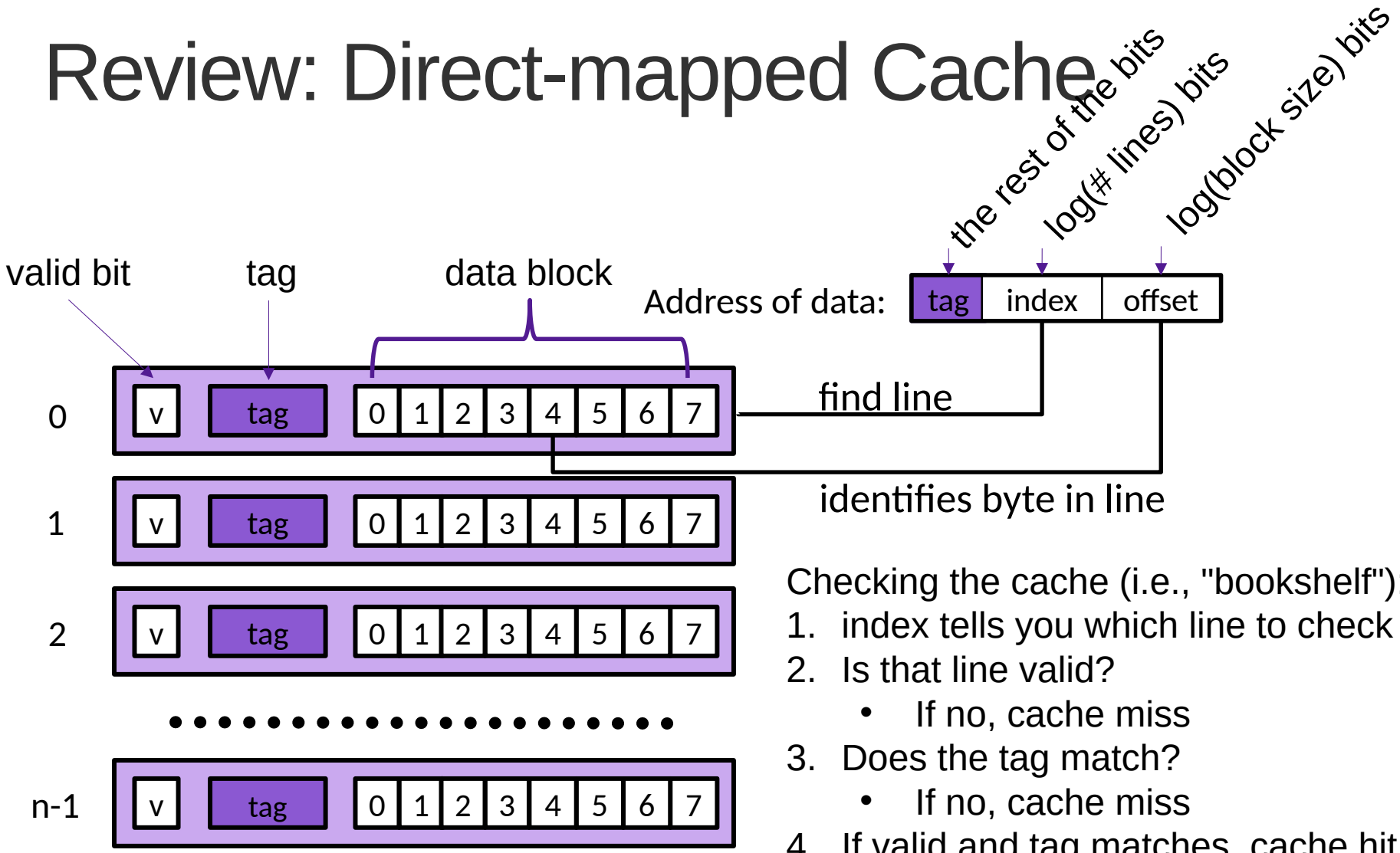
Review: Direct-mapped Cache



Checking the cache (i.e., "bookshelf"):

1. index tells you which line to check
2. Is that line valid?
   - If no, cache miss
3. Does the tag match?
   - If no, cache miss
4. If valid and tag matches, cache hit!

Review: Direct-mapped Cache



Checking the cache (i.e., "bookshelf"):

1. index tells you which line to check
2. Is that line valid?
   - If no, cache miss
3. Does the tag match?
   - If no, cache miss
4. If valid and tag matches, cache hit!
   - Read from datablock at offset

Review: Handling Cache Miss

When a cache miss occurs update cache line at that index:

Review: Handling Cache Miss

Address of data: 0x74

When a cache miss occurs update cache line at that index:

Line 0	1	110	0F	12	AB	34	FF	FF	EA	68
Line 1	1	001	00	00	00	00	00	40	06	1D
Line 2	1	101	0D	00	00	00	2F	00	00	00
Line 3	0	001	00	11	22	33	44	55	66	77

Review: Handling Cache Miss

Address of data: 0x74

0111 0100

When a cache miss occurs update cache line at that index:

Line 0	1	110	0F	12	AB	34	FF	FF	EA	68
Line 1	1	001	00	00	00	00	00	40	06	1D
Line 2	1	101	0D	00	00	00	2F	00	00	00
Line 3	0	001	00	11	22	33	44	55	66	77

Review: Handling Cache Miss

Address of data: 0x74

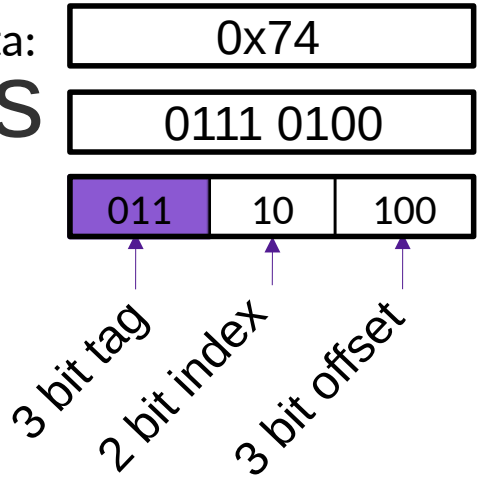
0111 0100

011	10	100
3 bit tag	2 bit index	3 bit offset

When a cache miss occurs update cache line at that index:

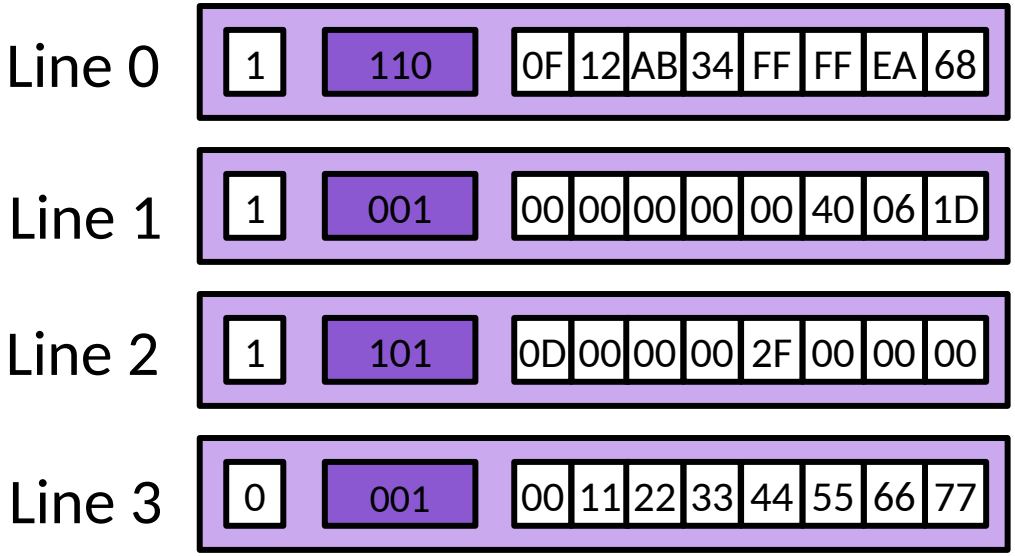
Line 0	1	110	0F	12	AB	34	FF	FF	EA	68
Line 1	1	001	00	00	00	00	00	40	06	1D
Line 2	1	101	0D	00	00	00	2F	00	00	00
Line 3	0	001	00	11	22	33	44	55	66	77

Review: Handling Cache Miss



When a cache miss occurs update cache line at that index:

1. Replace data block with bytes from memory
   - Copies all bytes with same tag + index



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Line 1	1	001	00	00	00	00	00	40	06	1D
Line 2	1	101	0D	00	00	00	2F	00	00	00
Line 3	0	001	00	11	22	33	44	55	66	77

0x79	23
0x78	B7
0x77	64
0x76	15
0x75	E0
0x74	AB
0x73	1A
0x72	47
0x71	33
0x70	2F
0x6F	0A
0x6E	00

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Line 0	1	110	0F	12	AB	34	FF	FF	EA	68
Line 1	1	001	00	00	00	00	00	40	06	1D
Line 2	1	101	2F	33	47	1A	AB	E0	15	64
Line 3	0	001	00	11	22	33	44	55	66	77

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Review: Handling Cache Miss

Address of data: 0x74

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011	10	100
3 bit tag	2 bit index	3 bit offset

When a cache miss occurs update cache line at that index:

1. Replace data block with bytes from memory
   - Copies all bytes with same tag + index
2. Update tag

Line 0	1	110	0F	12	AB	34	FF	FF	EA	68
Line 1	1	001	00	00	00	00	00	40	06	1D
Line 2	1	101	2F	33	47	1A	AB	E0	15	64
Line 3	0	001	00	11	22	33	44	55	66	77

0x79	23
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Line 0	1	110	0F	12	AB	34	FF	FF	EA	68
Line 1	1	001	00	00	00	00	00	40	06	1D
Line 2	1	011	2F	33	47	1A	AB	E0	15	64
Line 3	0	001	00	11	22	33	44	55	66	77

0x79	23
0x78	B7
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0x74	AB
0x73	1A
0x72	47
0x71	33
0x70	2F
0x6F	0A
0x6E	00

Review: Handling Cache Miss

Address of data: 0x74

0111 0100

011	10	100
3 bit tag	2 bit index	3 bit offset

When a cache miss occurs update cache line at that index:

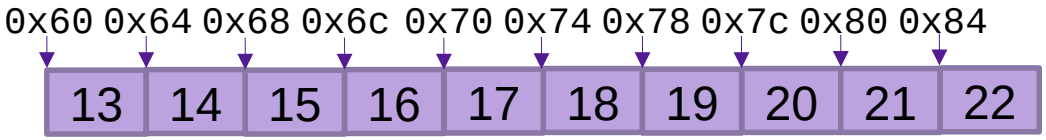
1. Replace data block with bytes from memory
   - Copies all bytes with same tag + index
2. Update tag
3. Set valid bit to 1 (if not already)

Line 0	1	110	0F	12	AB	34	FF	FF	EA	68
Line 1	1	001	00	00	00	00	00	40	06	1D
Line 2	1	011	2F	33	47	1A	AB	E0	15	64
Line 3	0	001	00	11	22	33	44	55	66	77

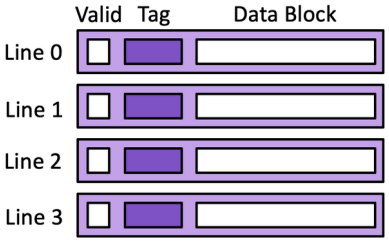
0x79	23
0x78	B7
0x77	64
0x76	15
0x75	E0
0x74	AB
0x73	1A
0x72	47
0x71	33
0x70	2F
0x6F	0A
0x6E	00

Review: Direct-mapped Cache Example

Memory



Cache



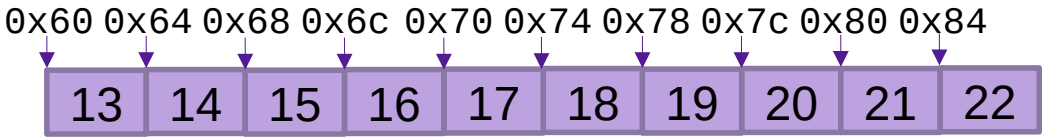
Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60					
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

Memory



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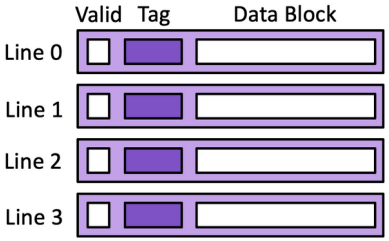

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60					
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

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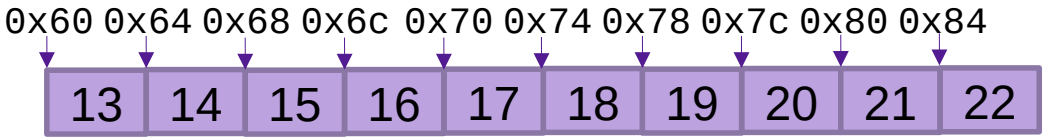

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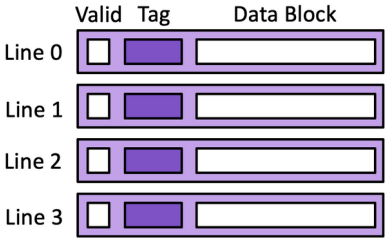

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000		
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

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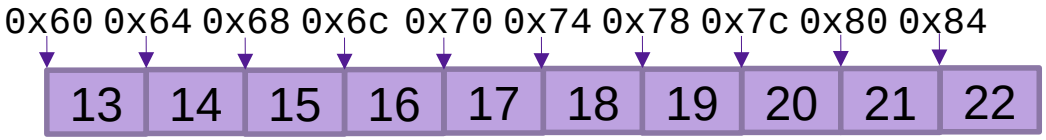

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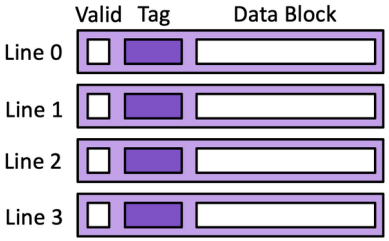


Assume 8 byte data blocks (fit 2 ints)

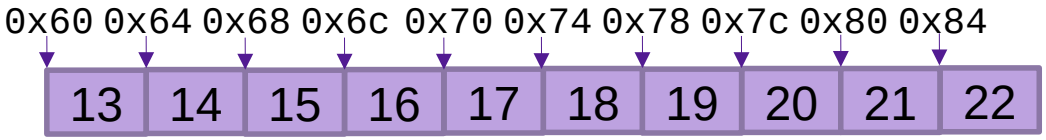
Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

Memory



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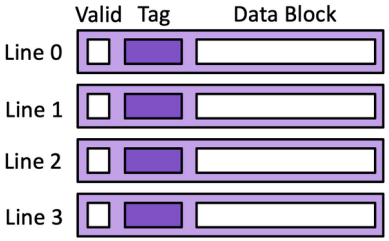

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

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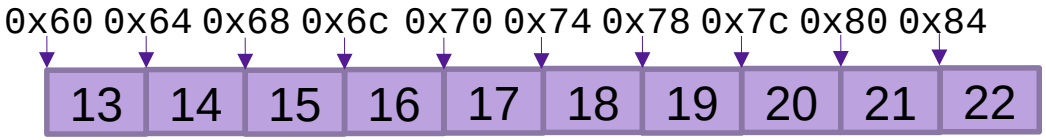

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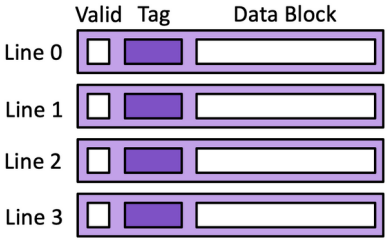

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
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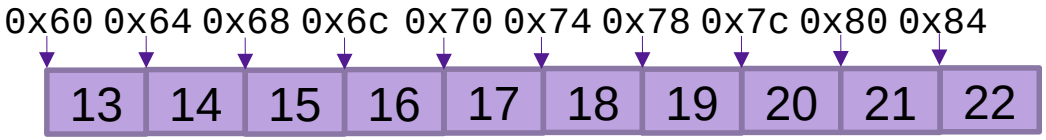

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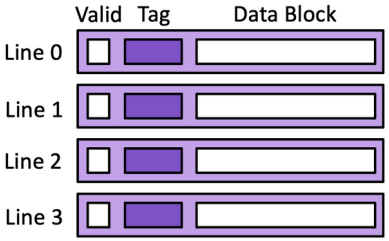

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100		
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54

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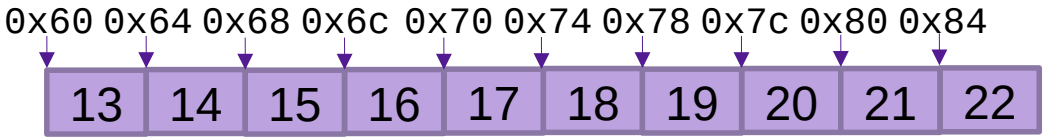

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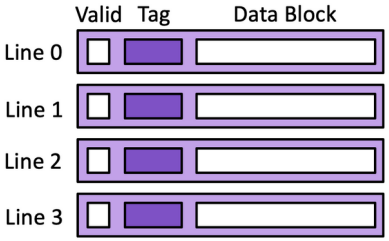


Assume 8 byte data blocks (fit 2 ints)

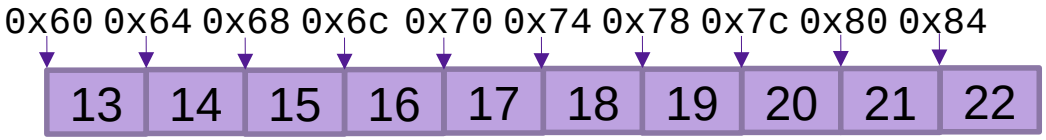
Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100	Hit	
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

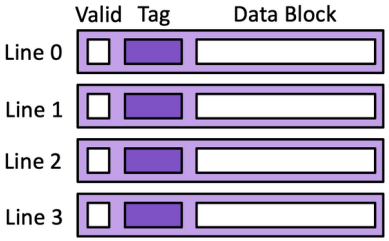
Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100	Hit	14
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

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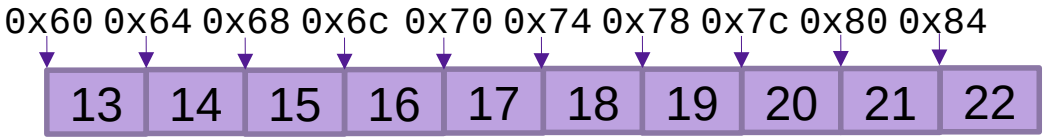

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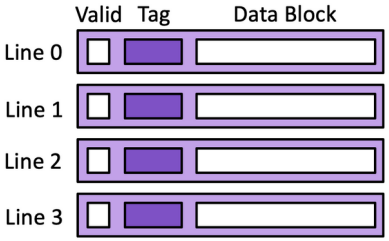

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Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100	Hit	14
rd 0x80	100=0x4	00	000		
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54
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Review: Direct-mapped Cache Example

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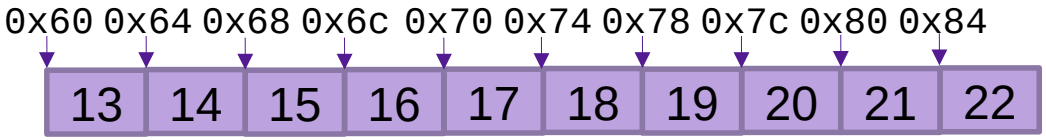

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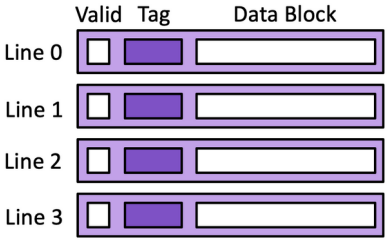

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rd 0x80	100=0x4	00	000	Miss	
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
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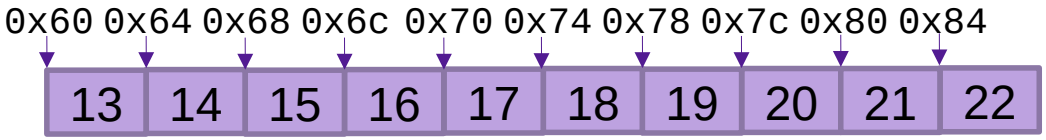

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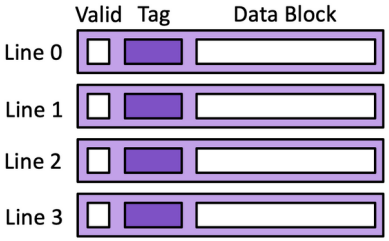

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rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54
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Review: Direct-mapped Cache Example

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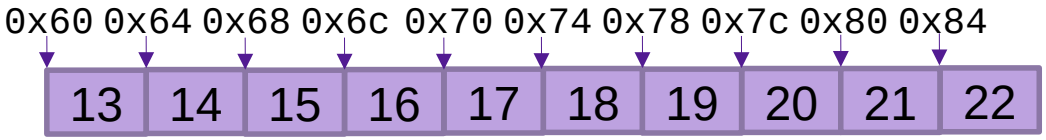

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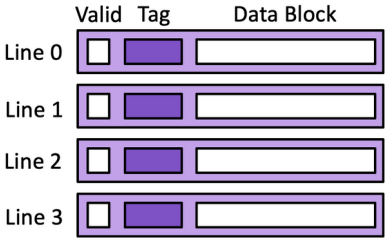

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rd 0x80	100=0x4	00	000	Miss	21
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
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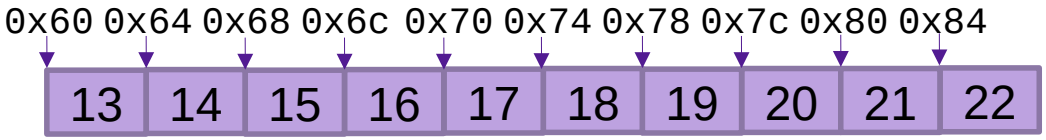

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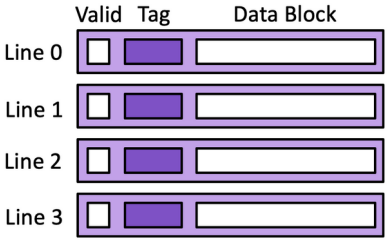

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rd 0x64					
rd 0x60					
rd 0x80					

Time

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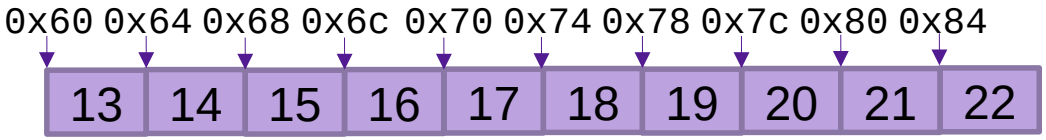

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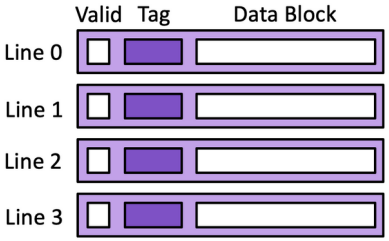

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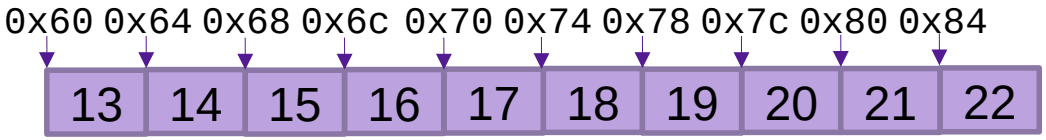

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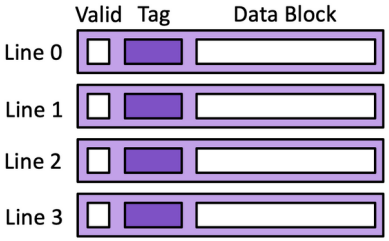

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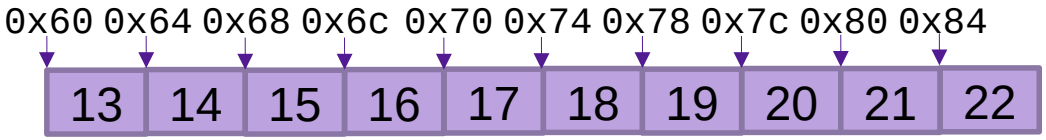

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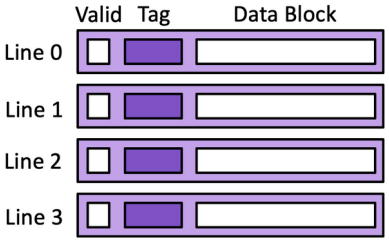

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rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
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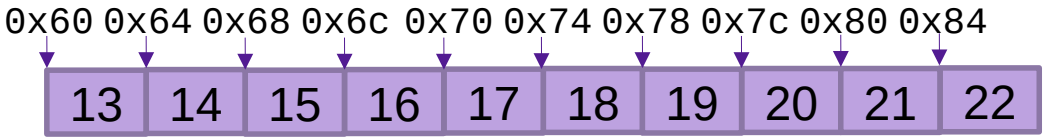

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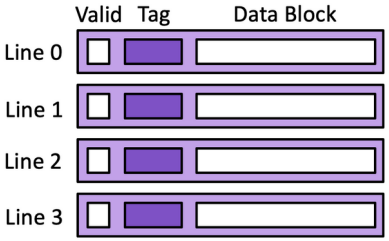

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rd 0x64	011=0x3	00	100	Miss	14
rd 0x64	011=0x3	00	100		
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
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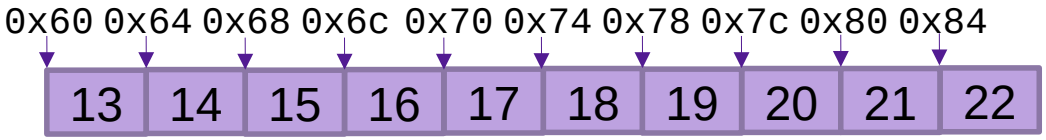

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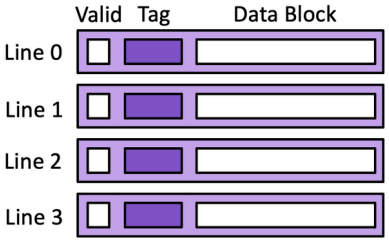

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rd 0x60					
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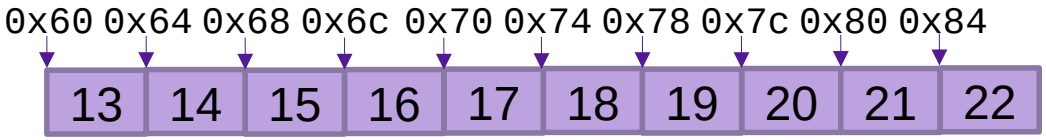

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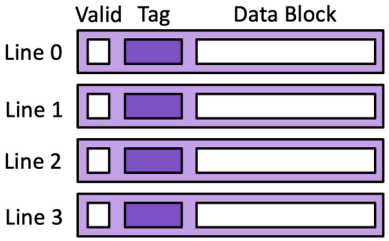

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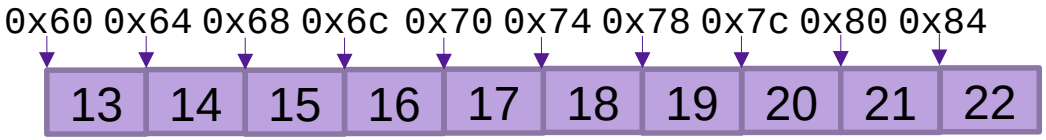

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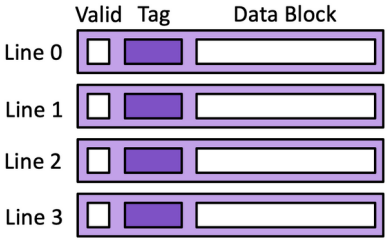

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rd 0x64	011=0x3	00	100	Hit	14
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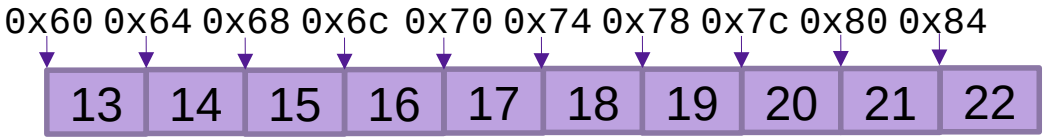

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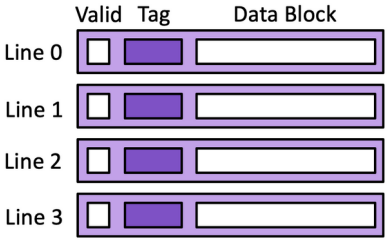

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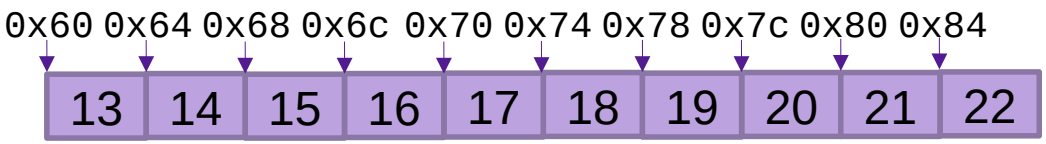
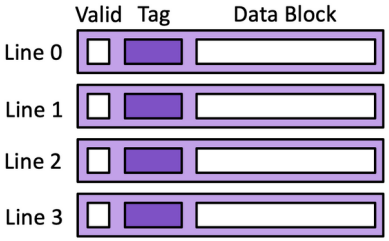
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100	Hit	14
rd 0x80	100=0x4	00	000	Miss	21
rd 0x64	011=0x3	00	100	Miss	14
rd 0x64	011=0x3	00	100	Hit	14
rd 0x60	011=0x3	00	000	Hit	13
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54
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Review: Direct-mapped Cache Example

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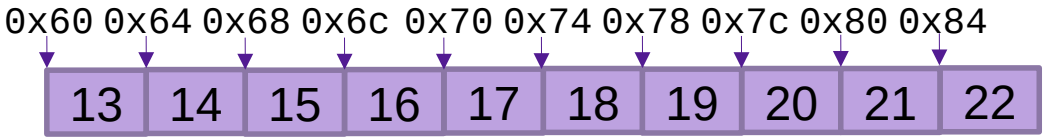
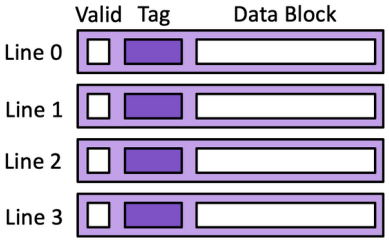


Cache



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Time

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Review: Direct-mapped Cache Example

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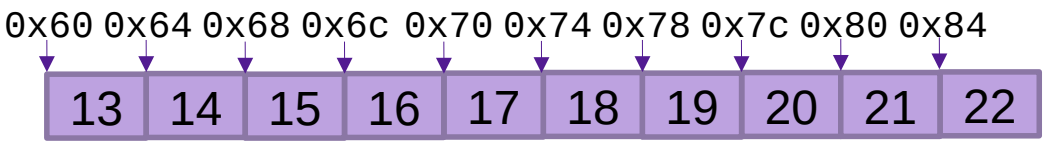

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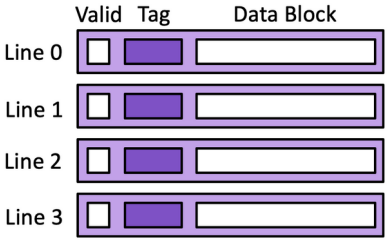

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Time

Line 0			Line 1			Line 2			Line 3		
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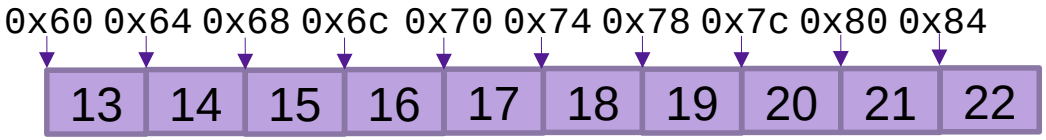

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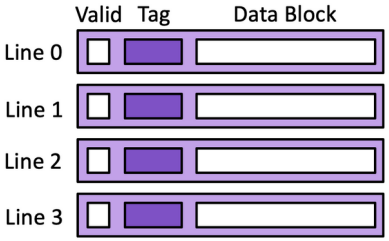

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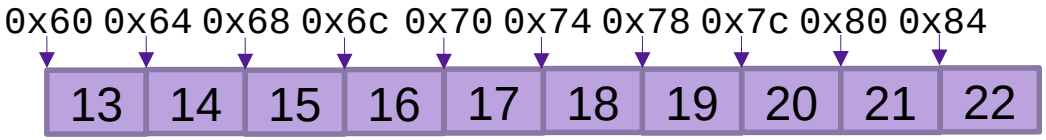

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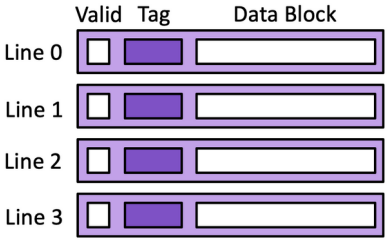

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Review: Direct-mapped Cache Example

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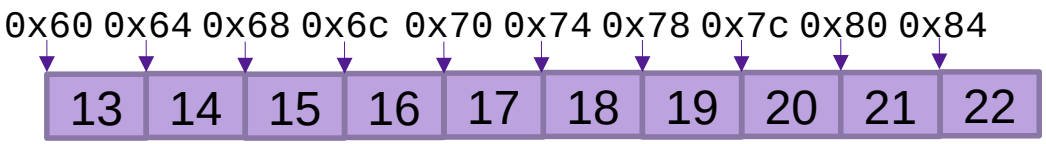

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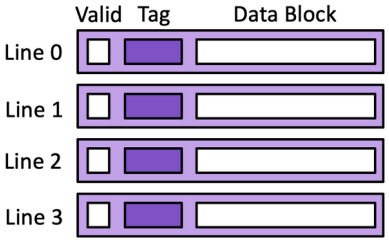

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1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54
1	4	21 22	0	8	49 50	0	a	51 52	0	1	53 54

How well does this take advantage of spatial locality?

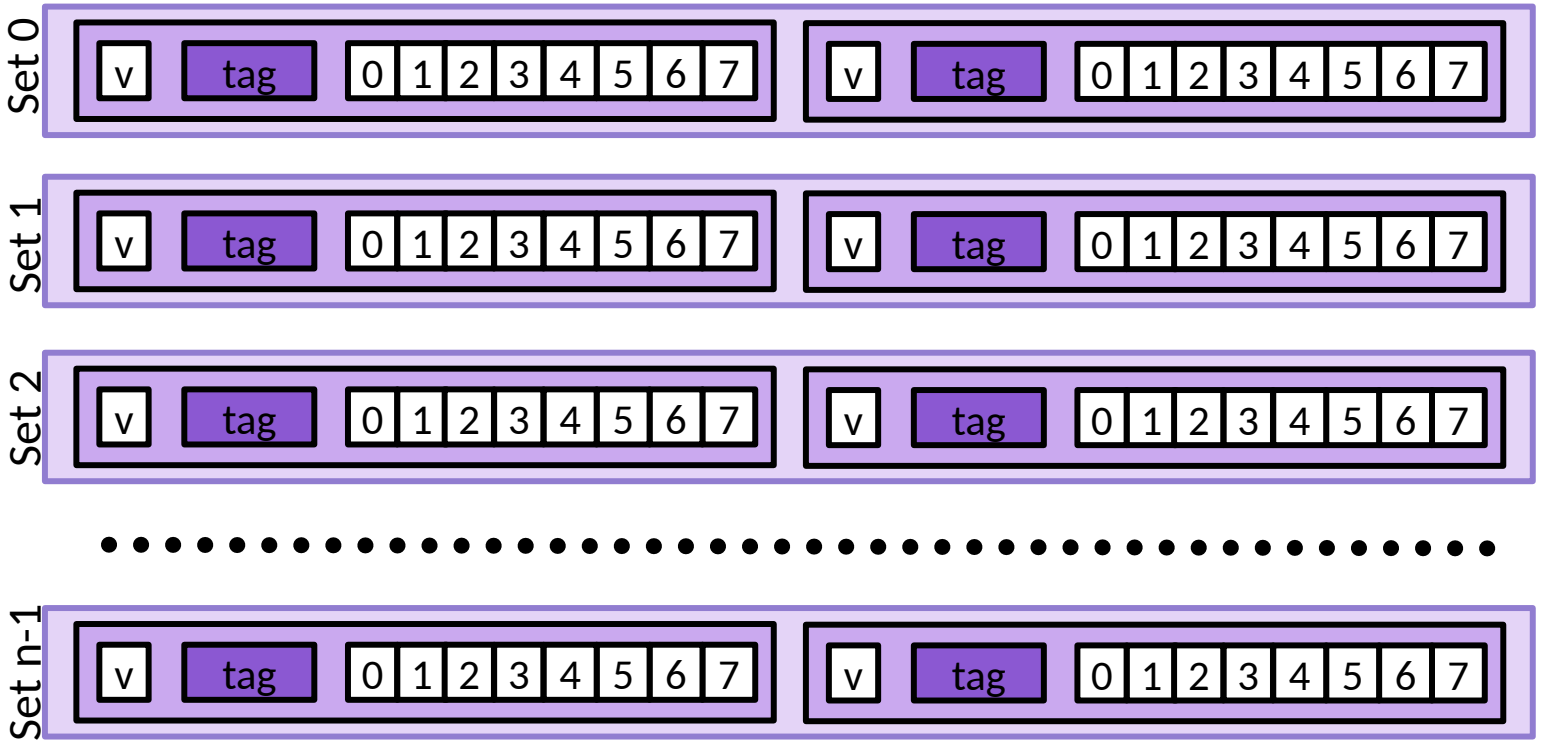
How well does this take advantage of temporal locality?

2-way Set Associative Cache

E = 2: Two lines per set

Assume: cache block size 8 bytes

Address of data:



2-way Set Associative Cache

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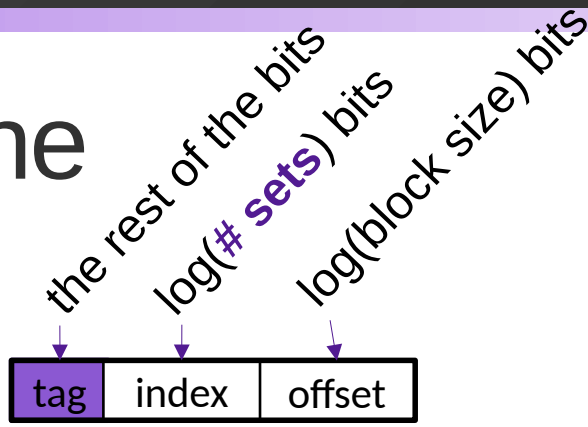
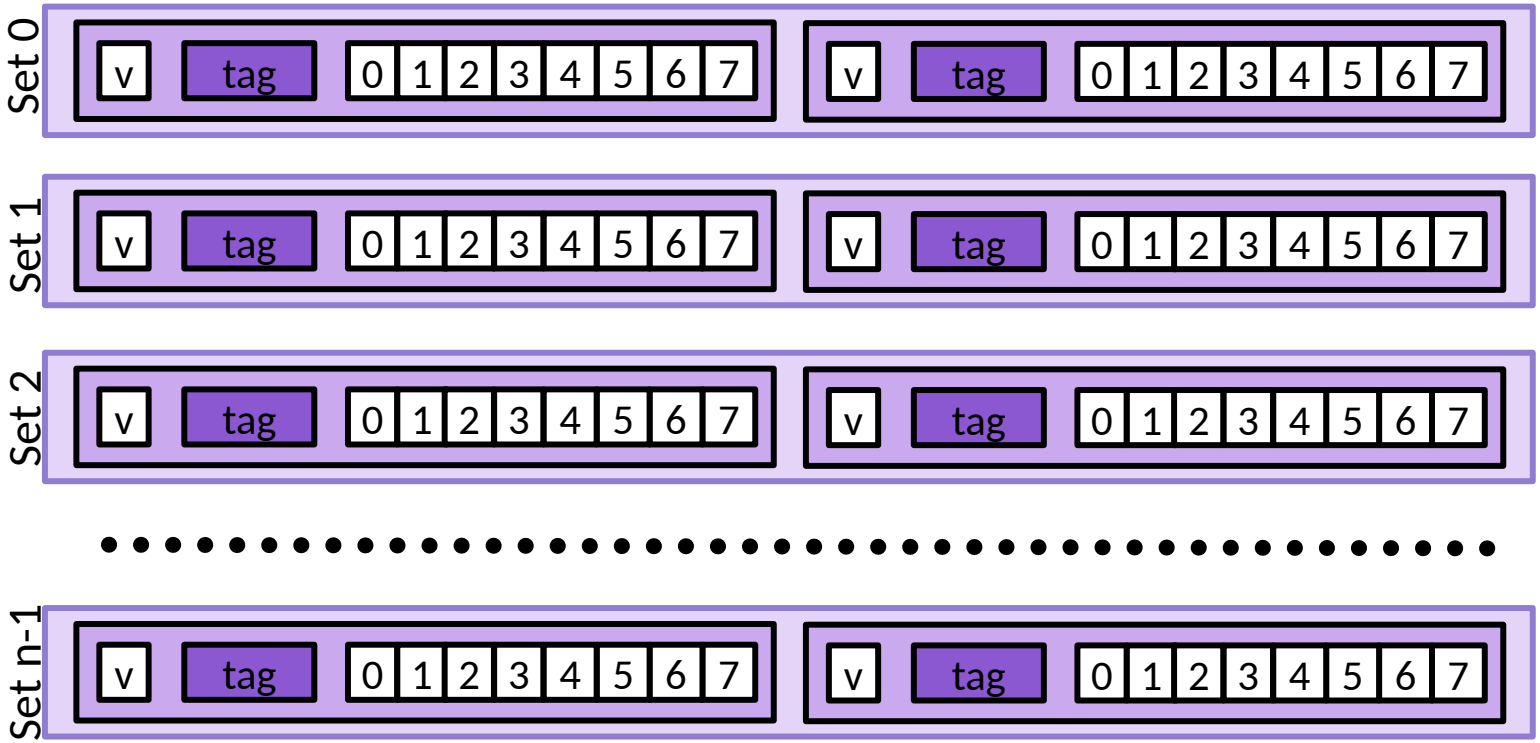
Address of data:

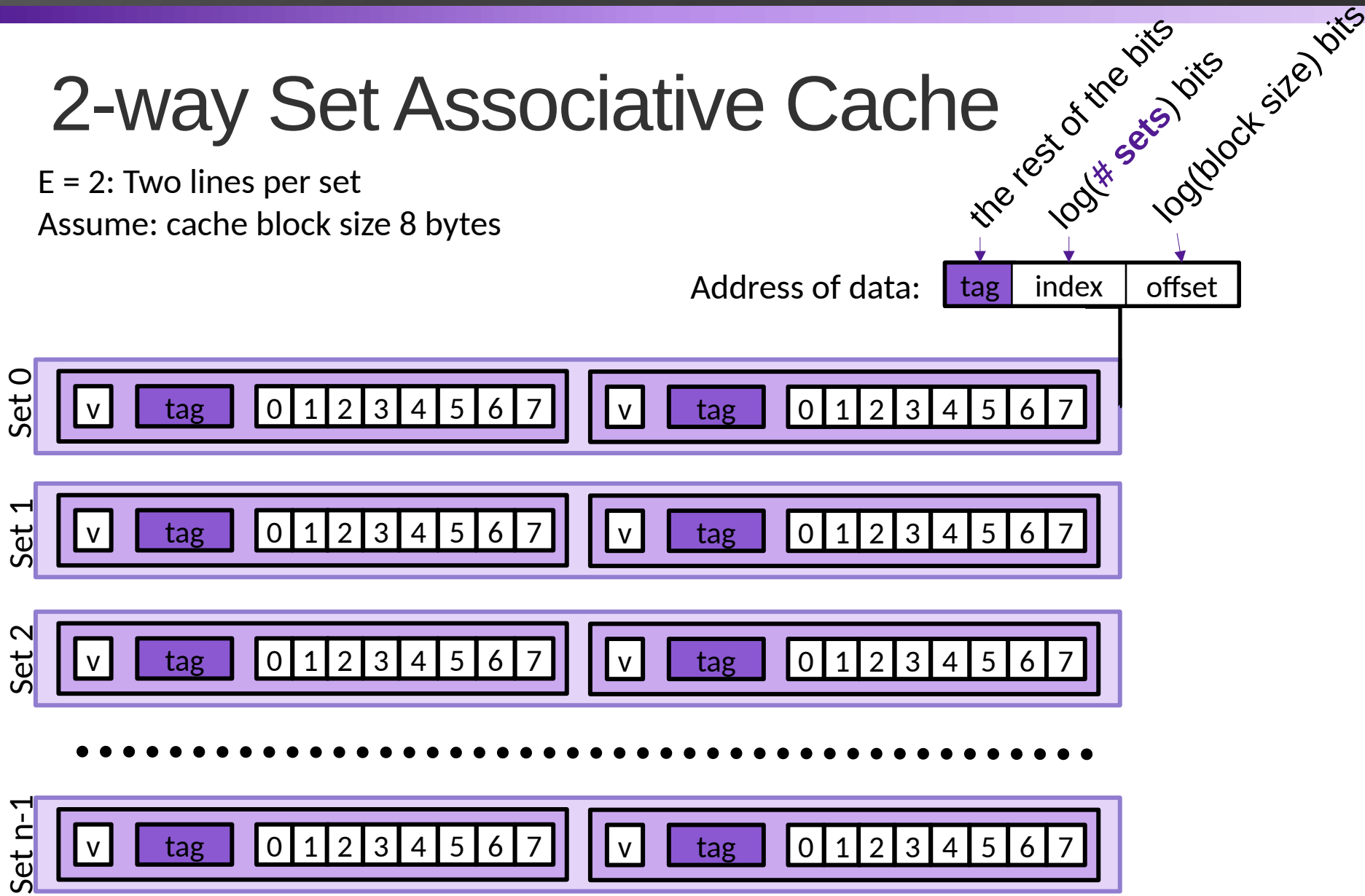




2-way Set Associative Cache

E = 2: Two lines per set

Assume: cache block size 8 bytes



2-way Set Associative Cache

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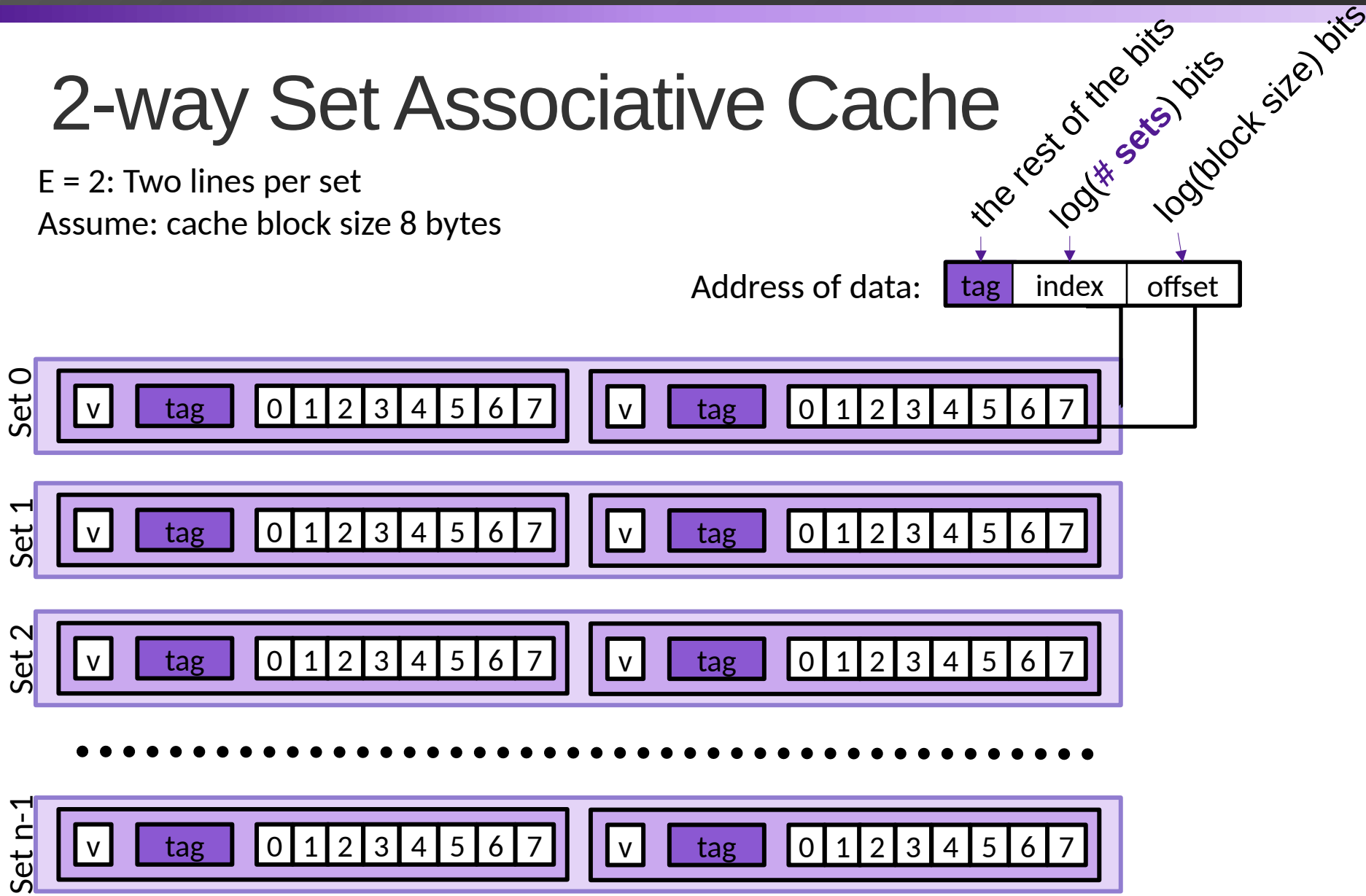
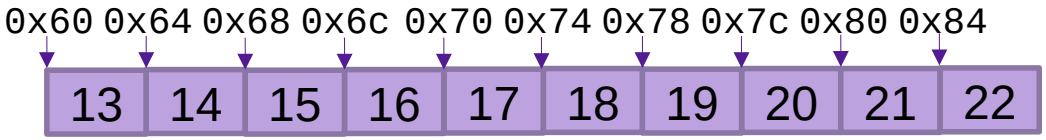


Review: Direct-mapped Cache Example

Memory



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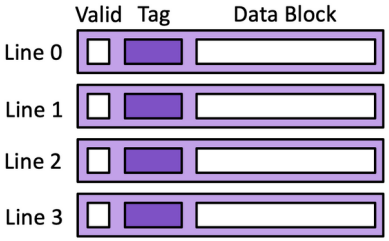

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60					
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

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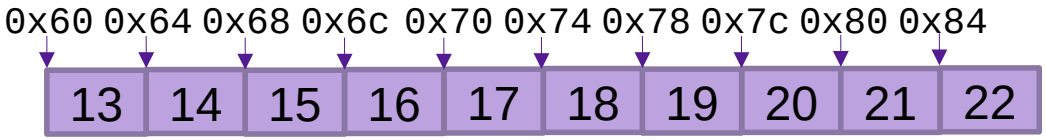

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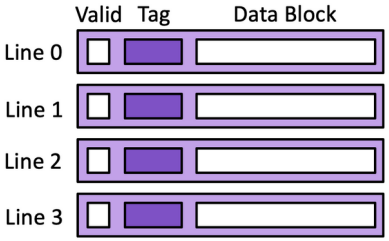

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Access	tag	idx	off	h/m	val
rd 0x60					
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

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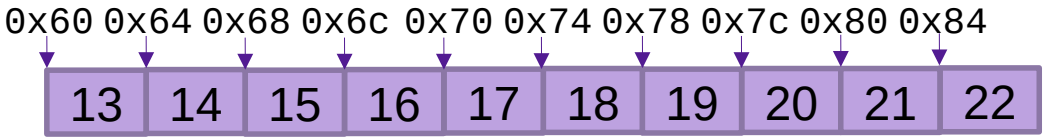

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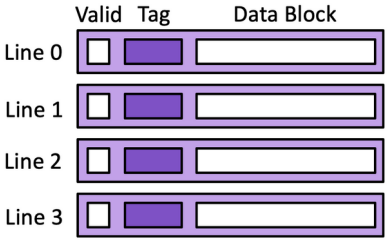

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000		
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

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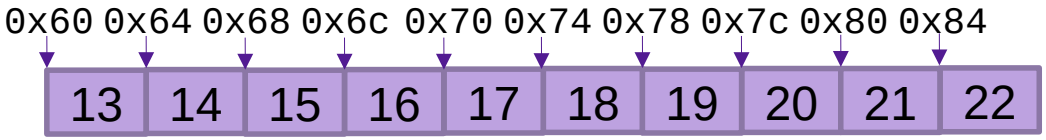

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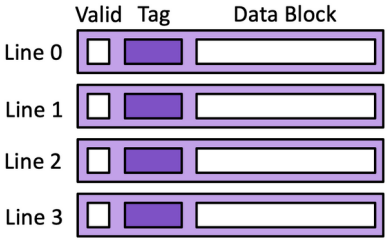

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

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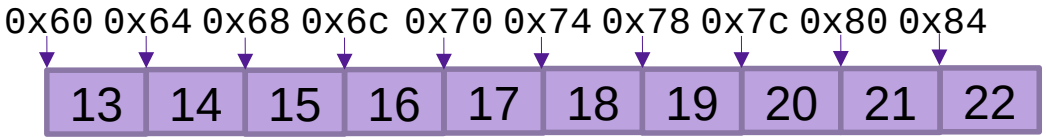

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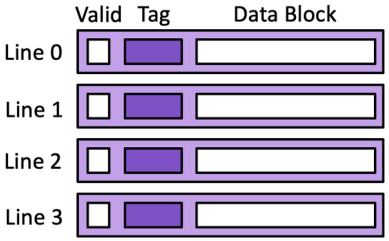

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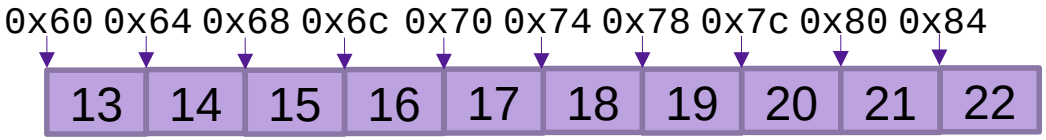

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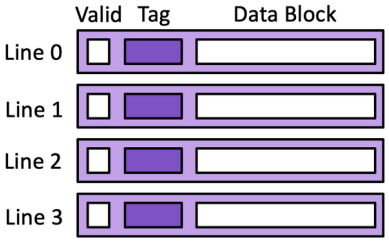

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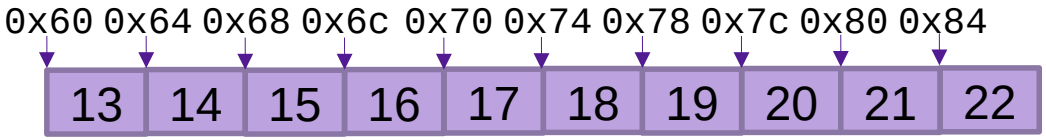

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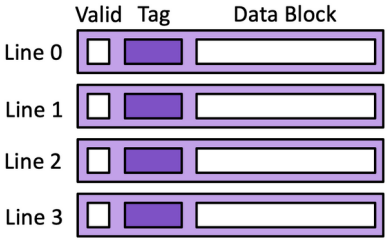


Assume 8 byte data blocks (fit 2 ints)

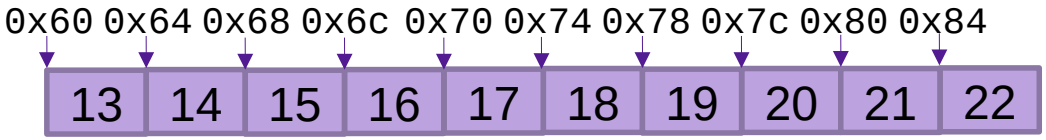
Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100		
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

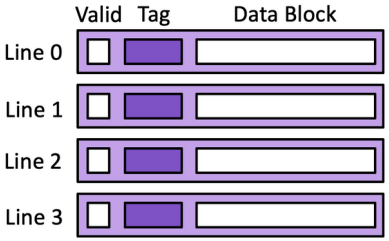
Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54

Review: Direct-mapped Cache Example

Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100	Hit	
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
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Review: Direct-mapped Cache Example

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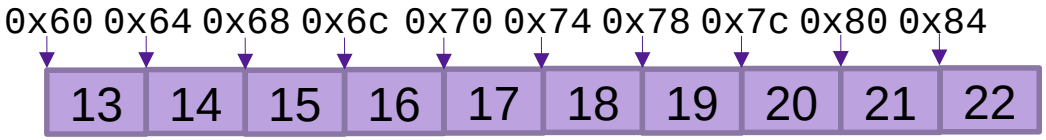

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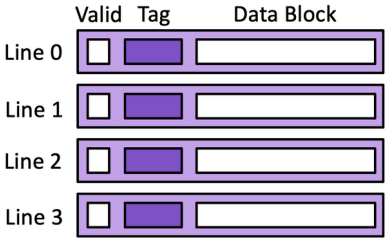

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rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
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Review: Direct-mapped Cache Example

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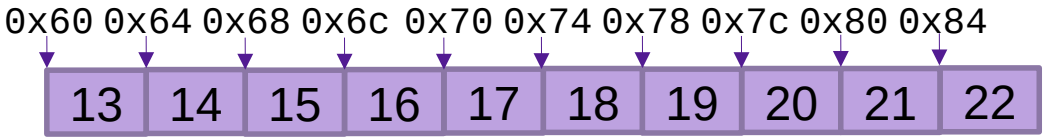

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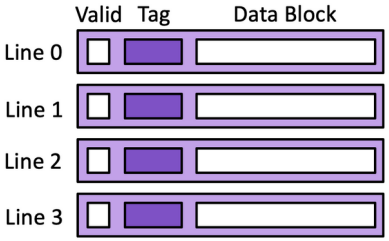

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rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100	Hit	14
rd 0x80	100=0x4	00	000		
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
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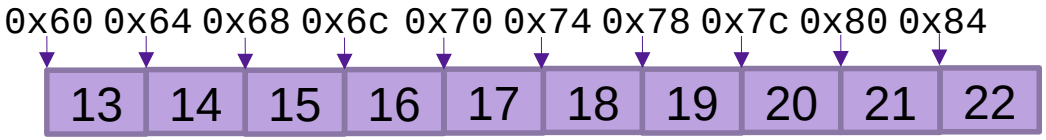

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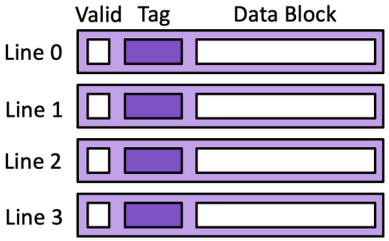

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rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

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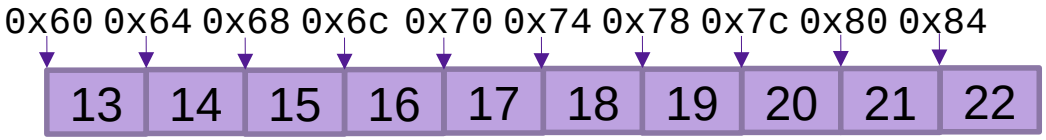

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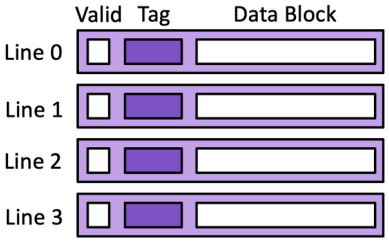

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rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
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Review: Direct-mapped Cache Example

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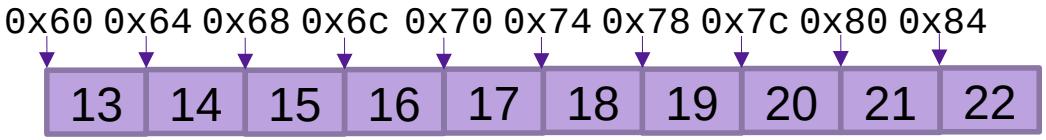

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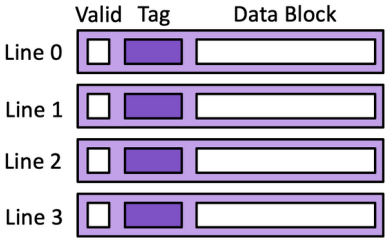

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rd 0x80					

Time

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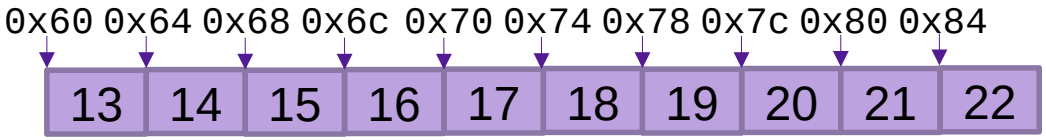

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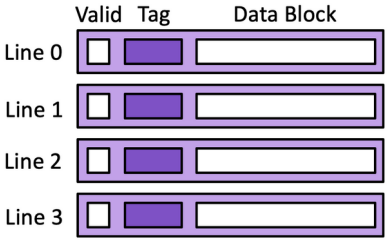

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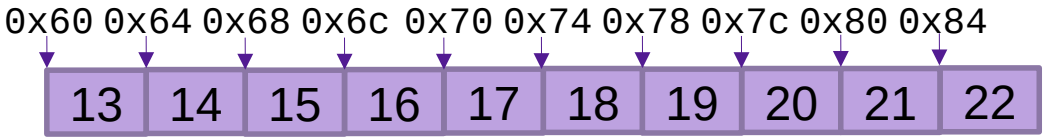

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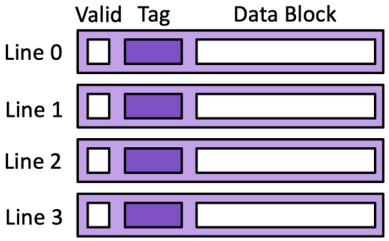

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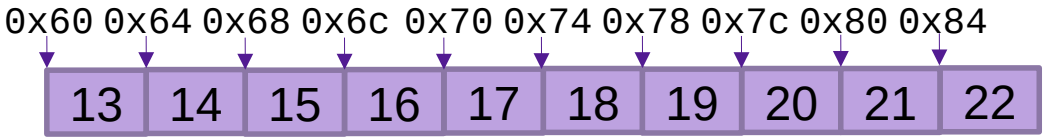

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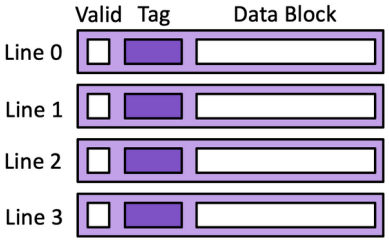

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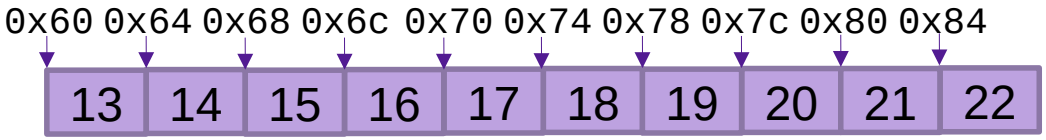

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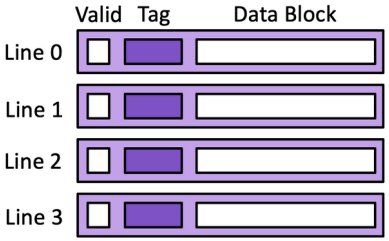

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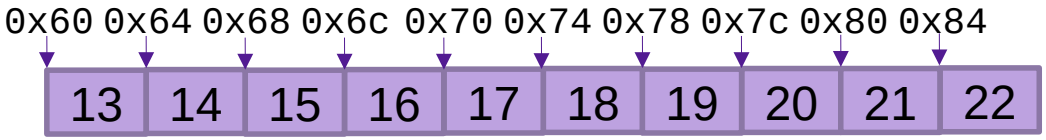

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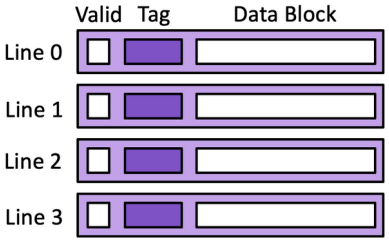

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Time

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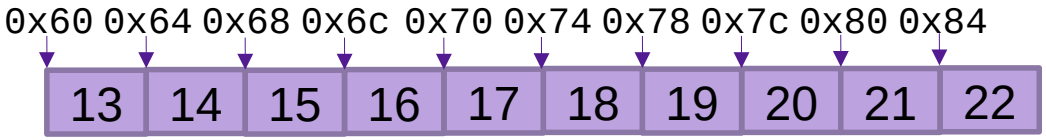

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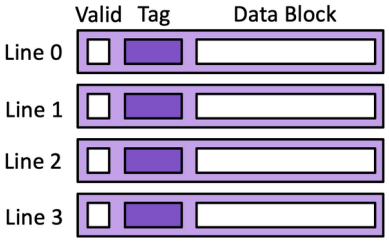

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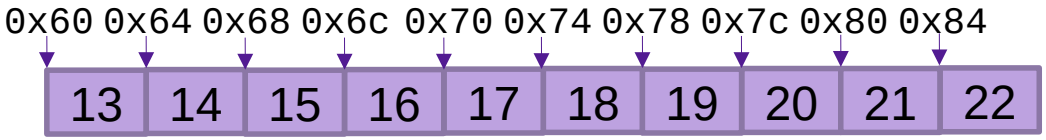

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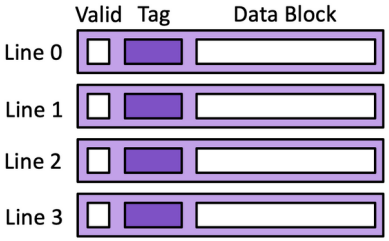

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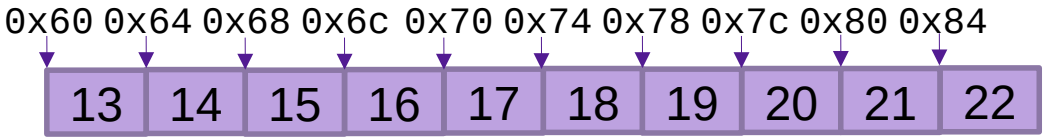

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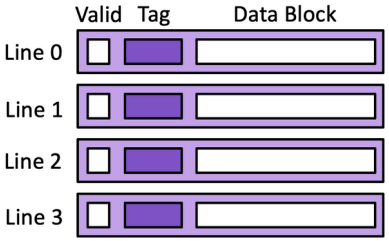

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rd 0x64	011=0x3	00	100	Hit	14
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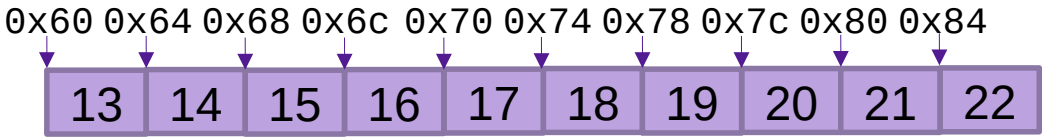
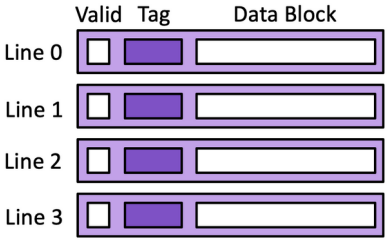
Review: Direct-mapped Cache Example

Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	011=0x3	00	000	Miss	13
rd 0x64	011=0x3	00	100	Hit	14
rd 0x80	100=0x4	00	000	Miss	21
rd 0x64	011=0x3	00	100	Miss	14
rd 0x64	011=0x3	00	100	Hit	14
rd 0x60	011=0x3	00	000	Hit	
rd 0x80					

Time

Line 0			Line 1			Line 2			Line 3		
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54
1	4	21 22	0	8	49 50	0	a	51 52	0	1	53 54
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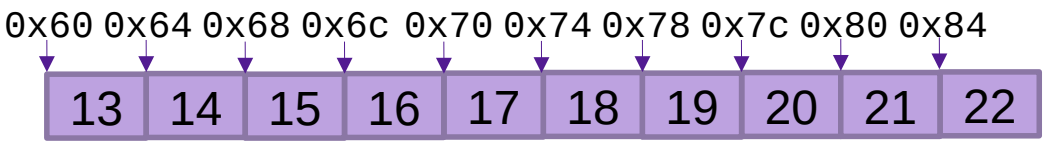
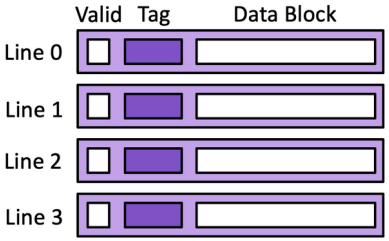


Cache



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rd 0x60	011=0x3	00	000	Hit	13
rd 0x80					

Time

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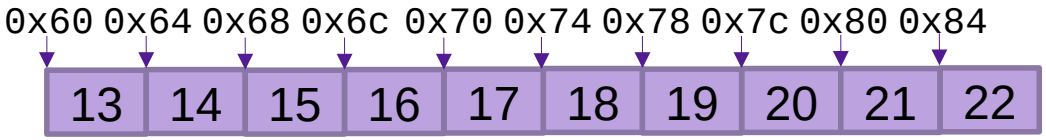

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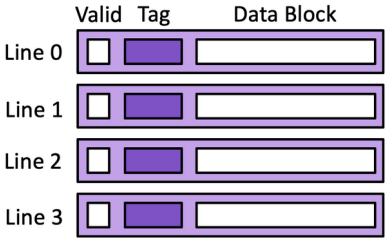

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Time

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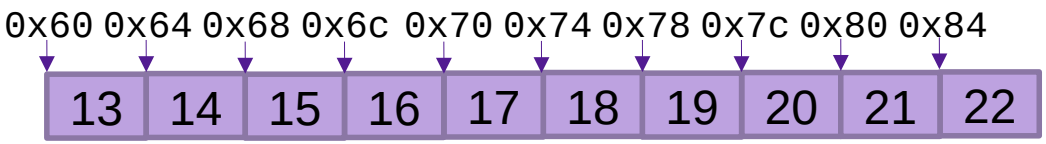

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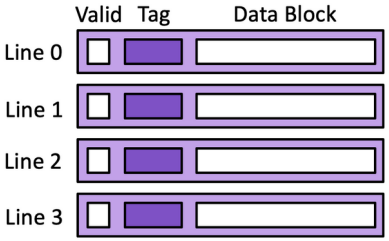

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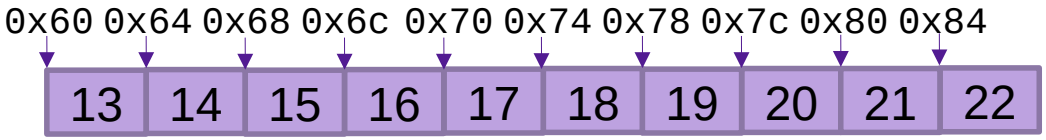

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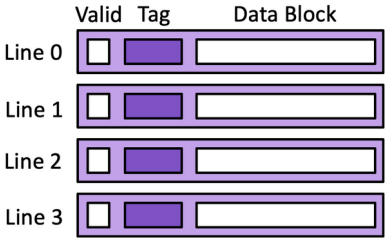

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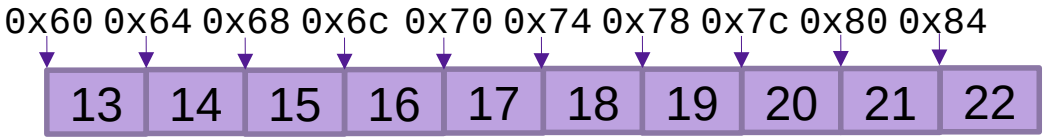

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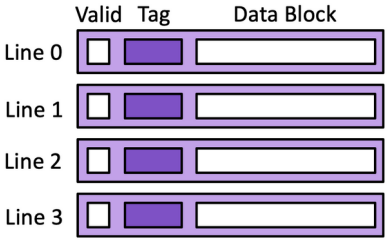

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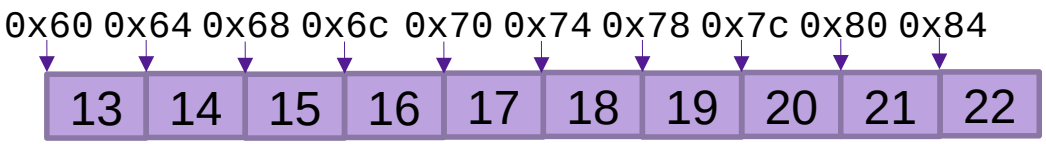

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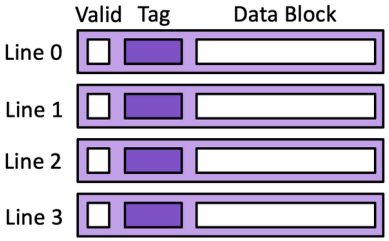

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rd 0x64	011=0x3	00	100	Hit	14
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Time

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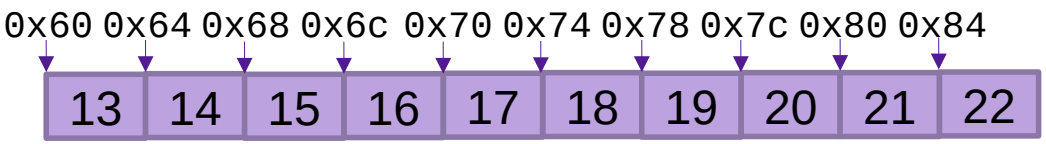
1	3	13 14	0	8	49 50	0	a	51 52	0	1	53 54
1	4	21 22	0	8	49 50	0	a	51 52	0	1	53 54

How well does this take advantage of spatial locality?

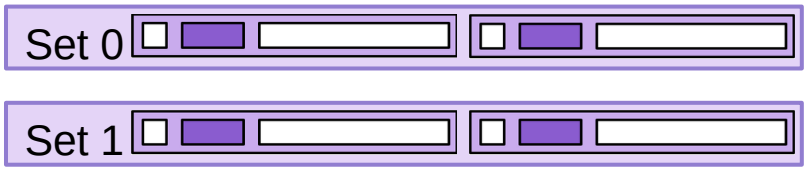
How well does this take advantage of temporal locality?

Exercise: 2-way Set Associative Cache

Memory



Cache



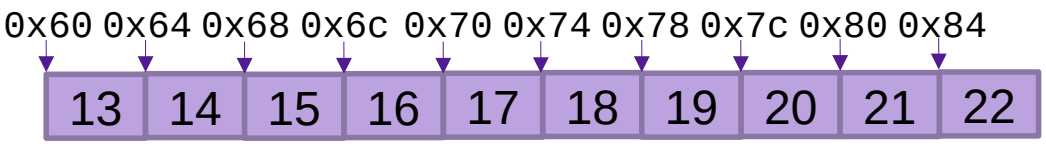
Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60					
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

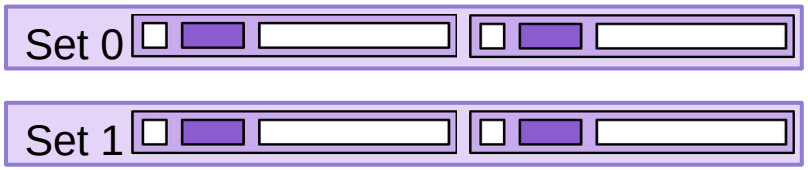
Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48

Exercise: 2-way Set Associative Cache

Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60					
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48

Exercise: 2-way Set Associative Cache

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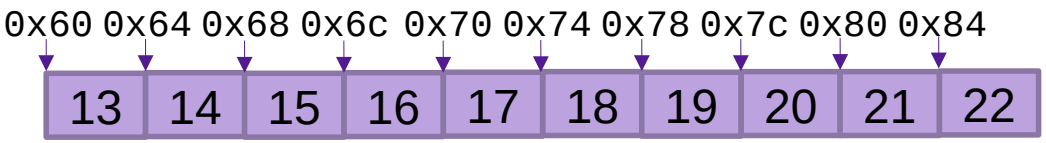

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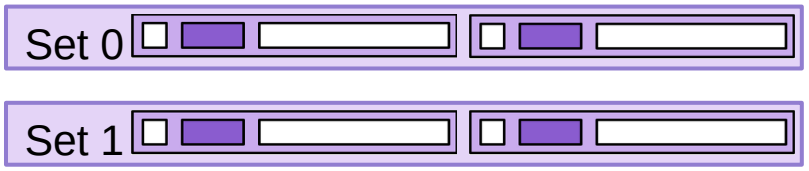


Assume 8 byte data blocks (fit 2 ints)

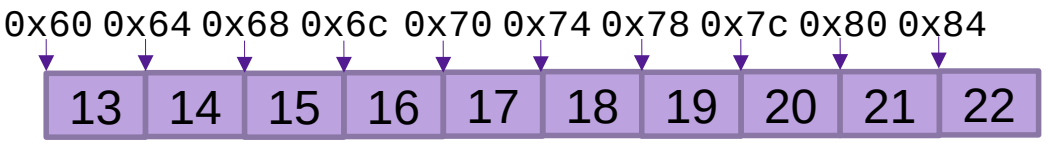
Access	tag	idx	off	h/m	val
rd 0x60					
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48

Exercise: 2-way Set Associative Cache

Memory



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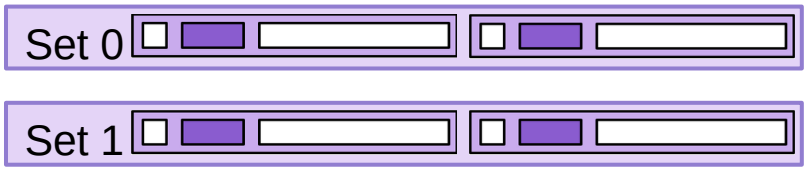


Assume 8 byte data blocks (fit 2 ints)

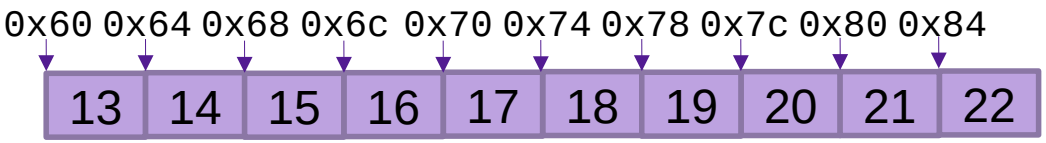
Access	tag	idx	off	h/m	val
rd 0x60	0110=0x6	0	000		
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48

Exercise: 2-way Set Associative Cache

Memory



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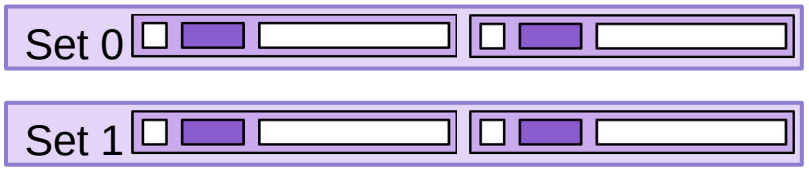

Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	0110=0x6	0	000	Miss	
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48

Exercise: 2-way Set Associative Cache

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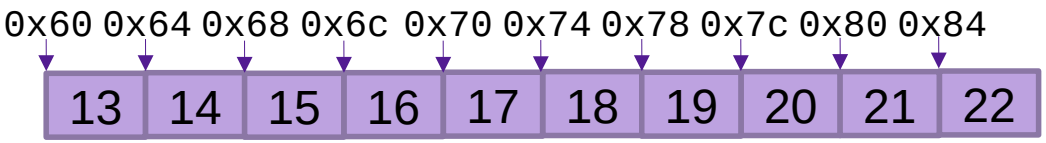

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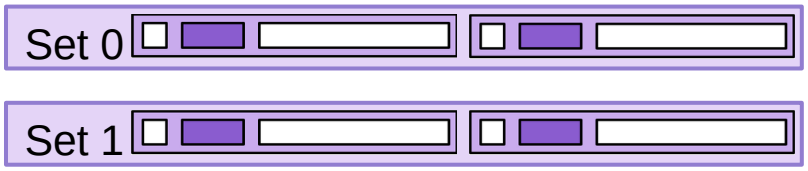

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rd 0x60	0110=0x6	0	000	Miss	
rd 0x64					
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rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48

Exercise: 2-way Set Associative Cache

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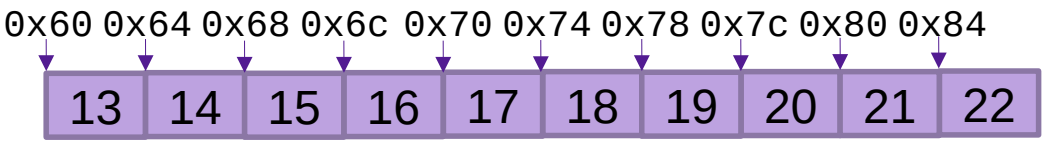

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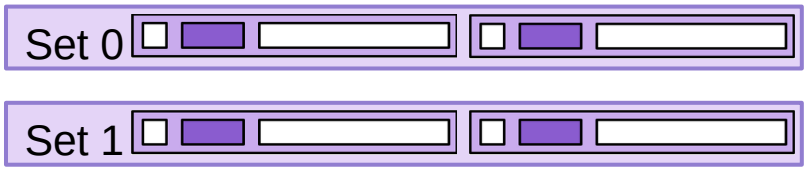

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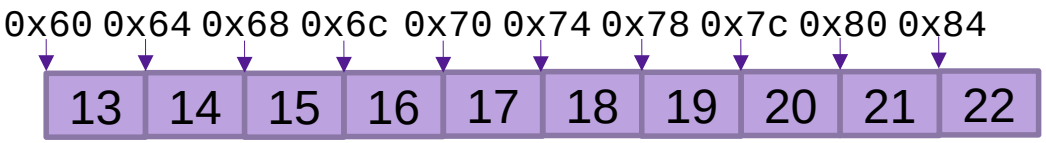
rd 0x80					

Time

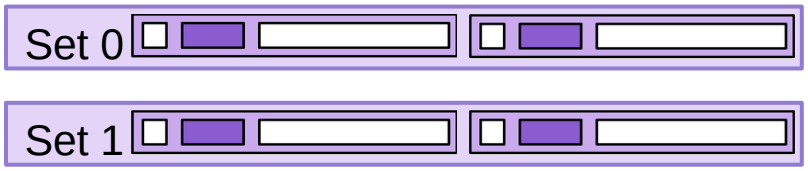
Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48

Exercise: 2-way Set Associative Cache

Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	0110=0x6	0	000	Miss	13
rd 0x64	0110=0x6	0	100		
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48

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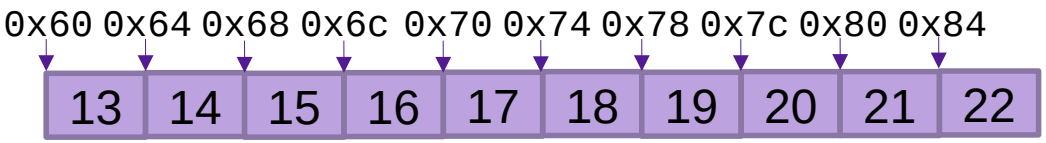

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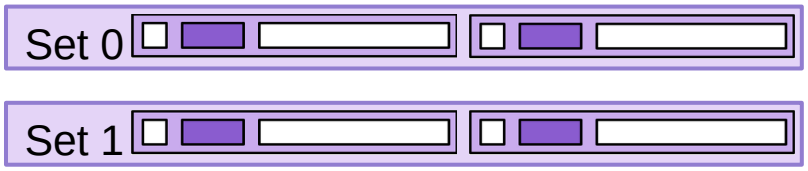

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rd 0x64	0110=0x6	0	100	Hit	
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
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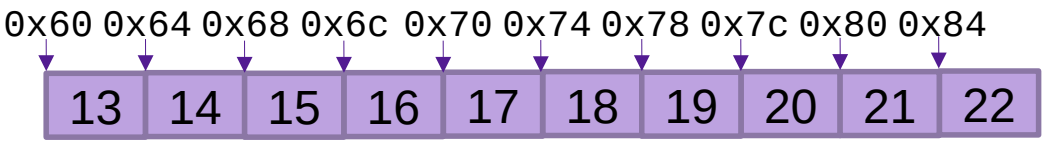

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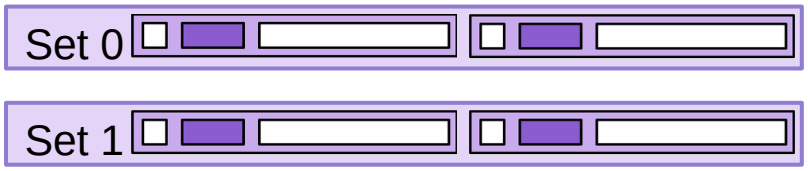

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Access	tag	idx	off	h/m	val
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rd 0x64	0110=0x6	0	100	Hit	14
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0								Set 1							
Line 0				Line 1				Line 0				Line 1			
0	0	47	48	0	1	47	48	0	0	47	48	0	1	47	48
1	6	13	14	0	1	47	48	0	0	47	48	0	1	47	48
1	6	13	14	0	1	47	48	0	0	47	48	0	1	47	48

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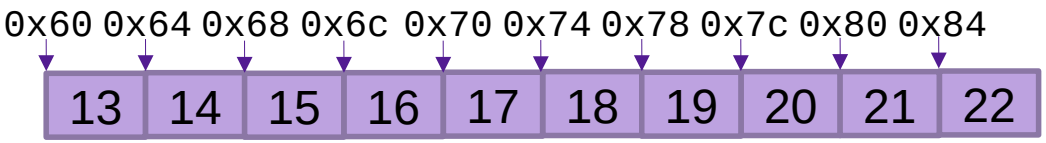

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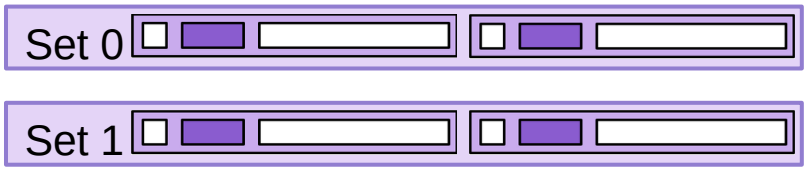

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rd 0x60	0110=0x6	0	000	Miss	13
rd 0x64	0110=0x6	0	100	Hit	14
rd 0x80	1000=0x8	0	000		
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
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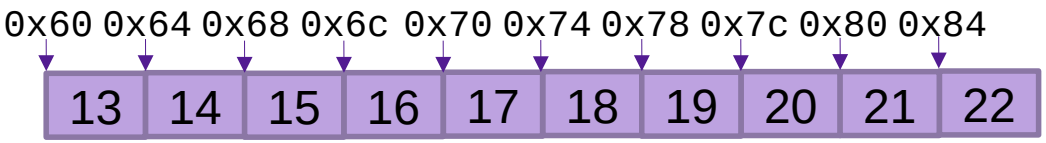

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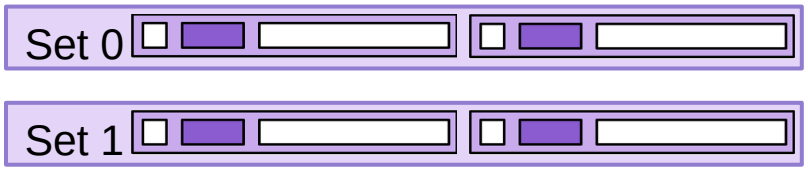

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rd 0x80	1000=0x8	0	000	Miss	
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
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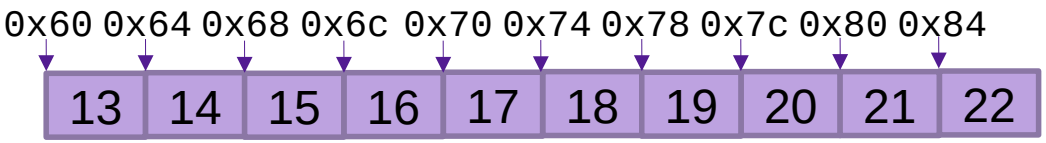

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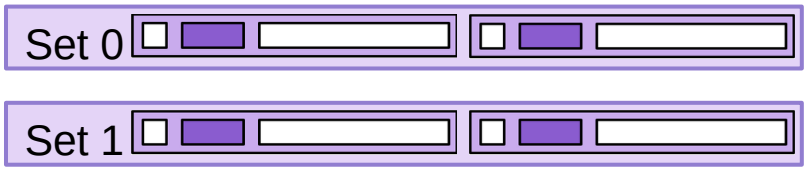

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rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48

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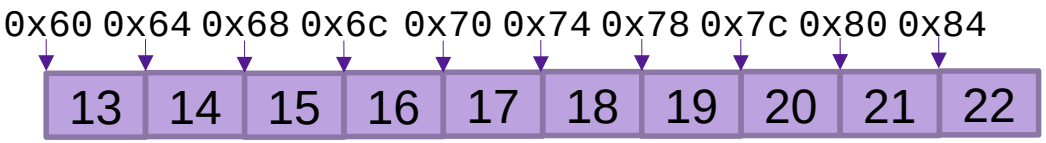

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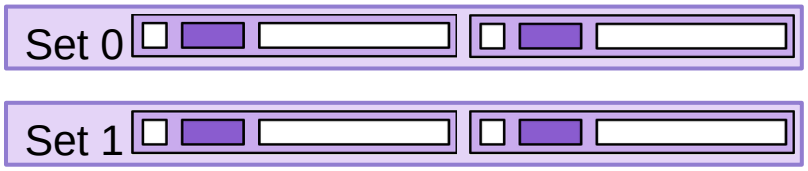

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rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
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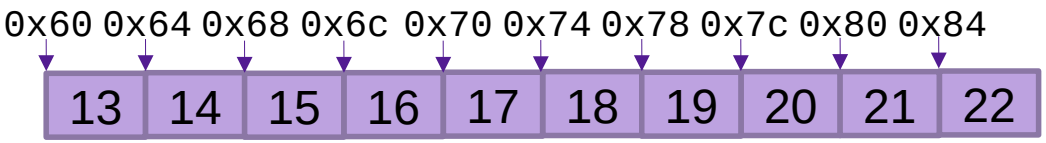

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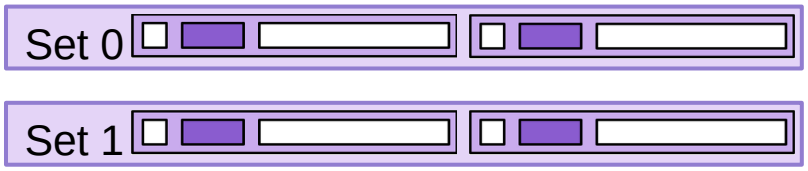

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rd 0x64					
rd 0x60					
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
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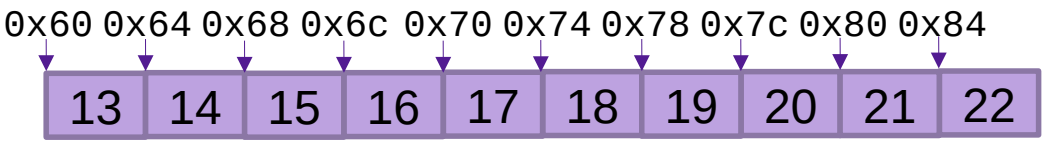

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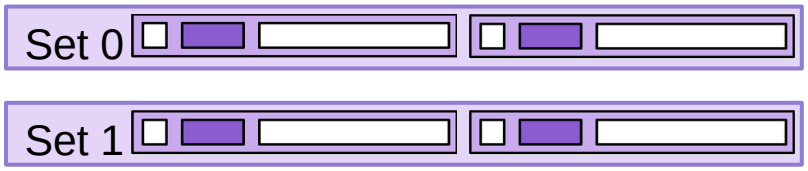

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0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
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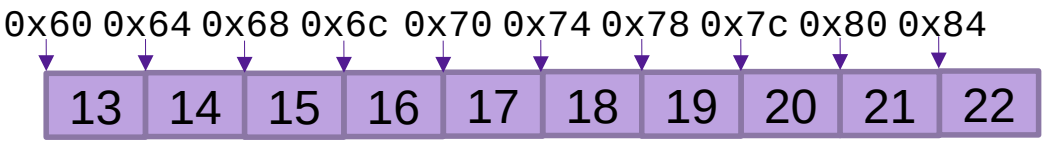

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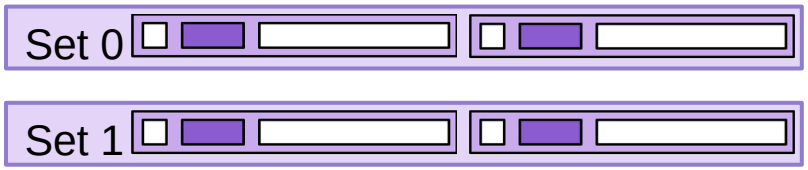

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rd 0x80					

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0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
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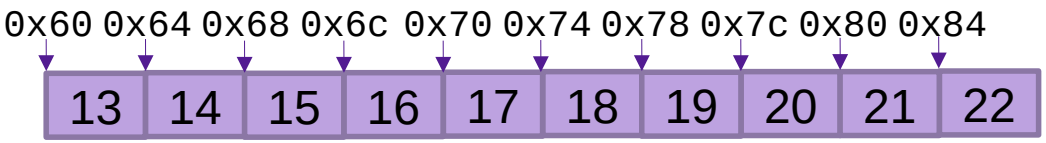

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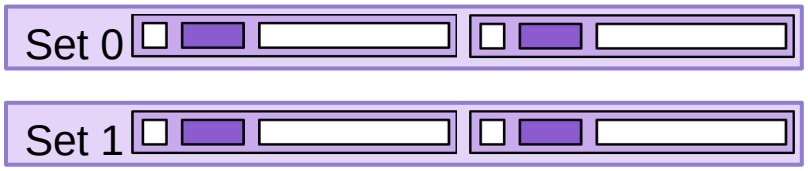

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rd 0x64	0110=0x6	0	100		
rd 0x60					
rd 0x80					

Time

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Line 0			Line 1			Line 0			Line 1		
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1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
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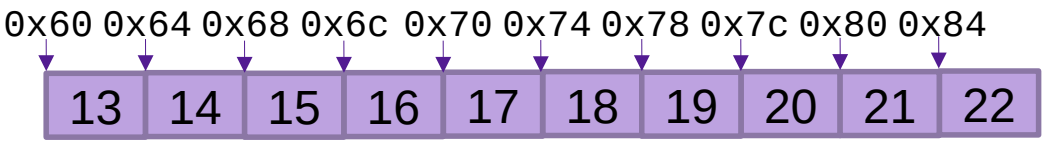

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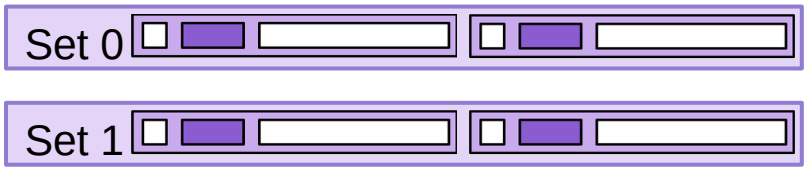

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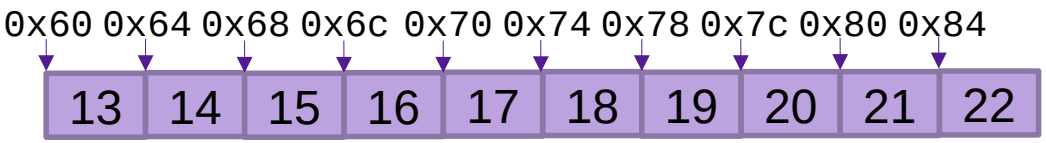

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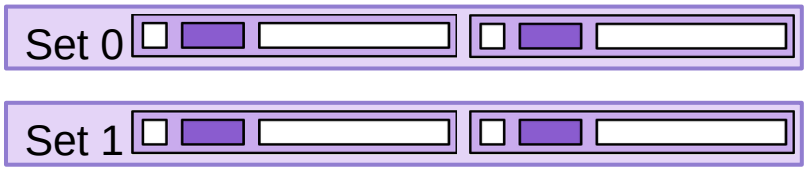

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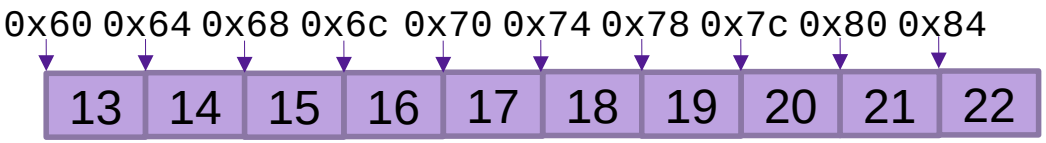

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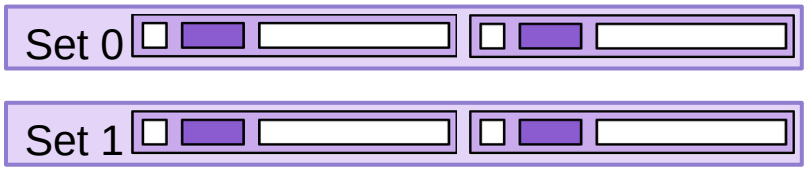

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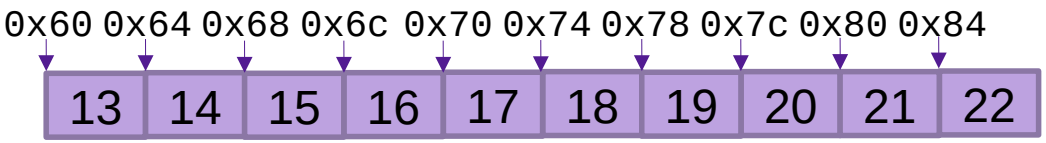
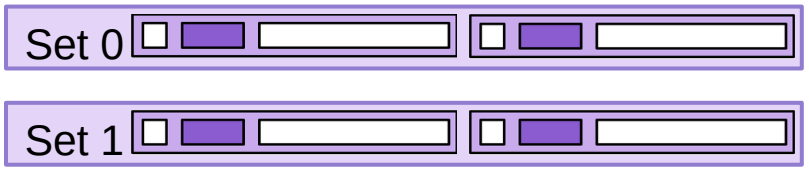
Exercise: 2-way Set Associative Cache

Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60	0110=0x6	0	000	Miss	13
rd 0x64	0110=0x6	0	100	Hit	14
rd 0x80	1000=0x8	0	000	Miss	21
rd 0x64	0110=0x6	0	100	Hit	14
rd 0x64	0110=0x6	0	100	Hit	14
rd 0x60	0110=0x6	0	000	Hit	
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
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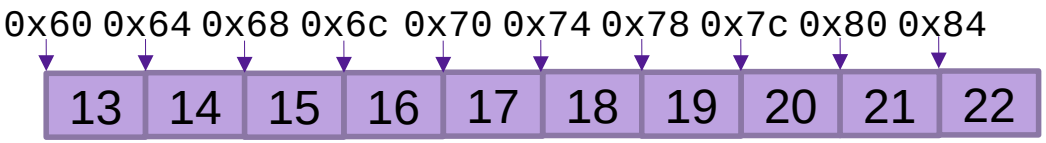
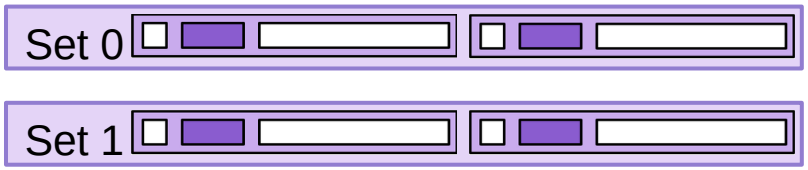


Cache



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rd 0x64	0110=0x6	0	100	Hit	14
rd 0x60	0110=0x6	0	000	Hit	13
rd 0x80					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
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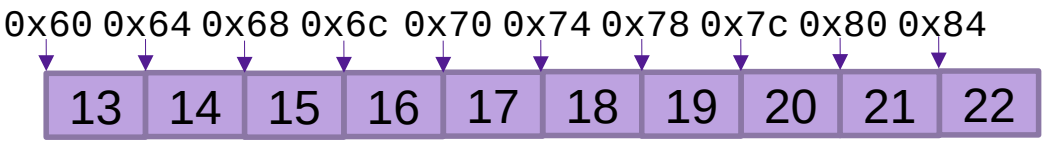

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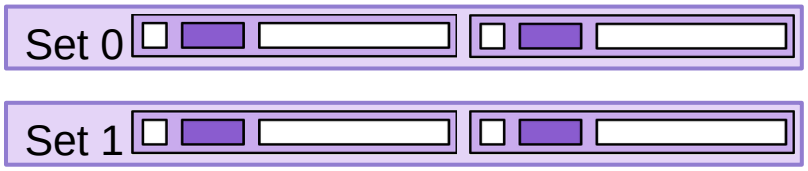

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Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
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1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
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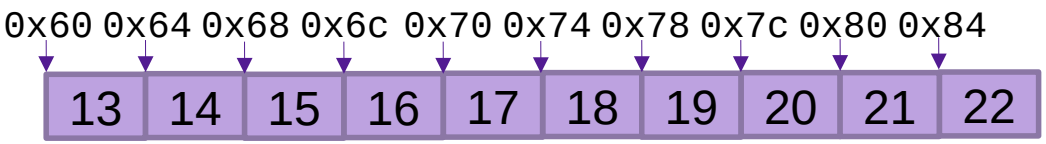

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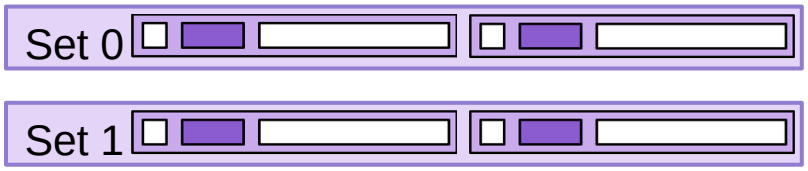

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Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
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1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
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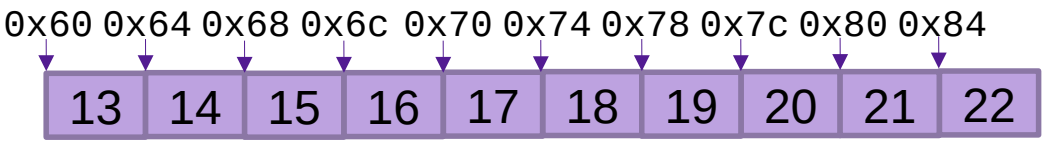

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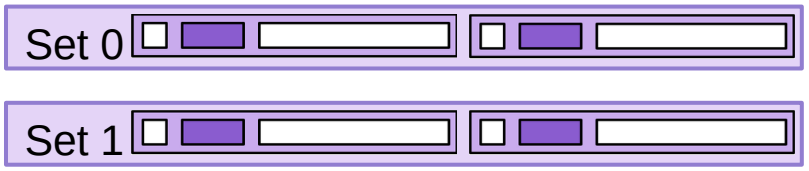

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Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
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1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
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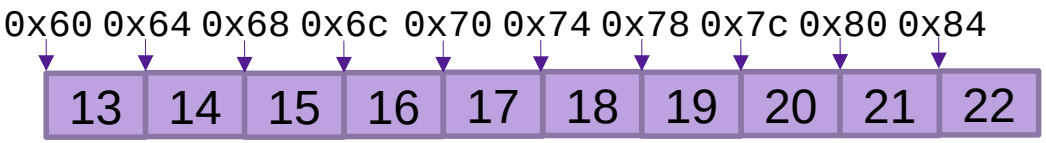

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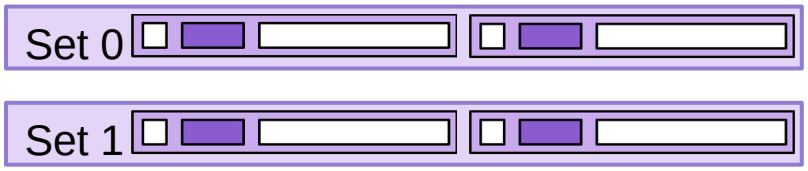

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rd 0x60	0110=0x6	0	000	Hit	13
rd 0x80	1000=0x8	0	000	Hit	21
rd 0x70					

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
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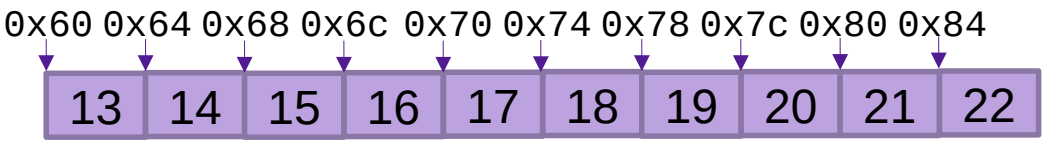

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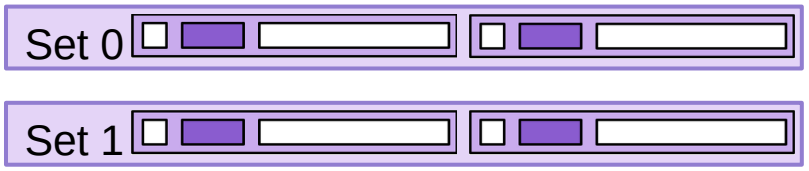

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rd 0x60	0110=0x6	0	000	Hit	13
rd 0x80	1000=0x8	0	000	Hit	21
rd 0x70	0111=0x7	0	000		

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
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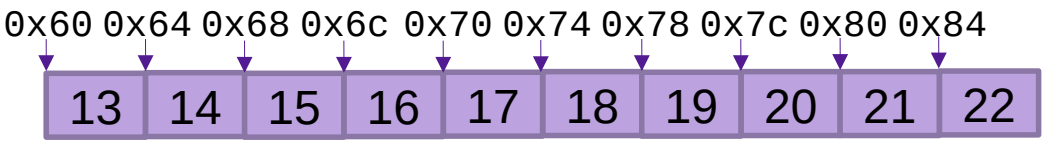

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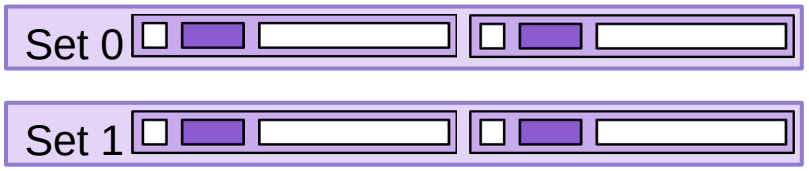

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rd 0x60	0110=0x6	0	000	Hit	13
rd 0x80	1000=0x8	0	000	Hit	21
rd 0x70	0111=0x7	0	000	Miss	

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48

Eviction from the Cache

On a cache miss, a new block is loaded into the cache

- Direct-mapped cache: A valid block at the same location must be evicted—no choice
- Associative cache: If all blocks in the set are valid, one must be evicted

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  - Most-recently used; requires extra data in each set
  - Most-frequently used; requires extra data in each set

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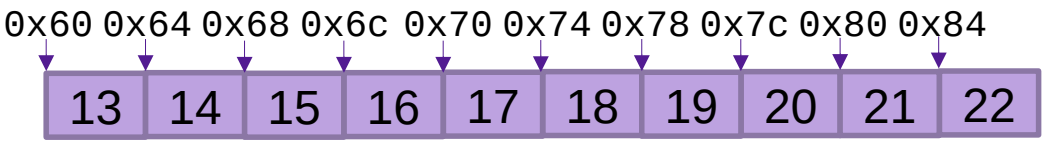
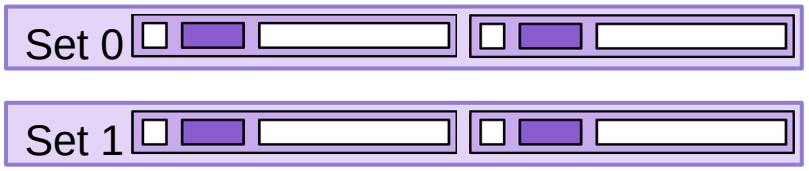
Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

Access	tag	idx	off	h/m	val
rd 0x60					
rd 0x64					
rd 0x80					
rd 0x64					
rd 0x64					
rd 0x60					
rd 0x80					
rd 0x70					

Time

Set 0							Set 1						
Line 0				Line 1			Line 0				Line 1		
0	0	47	48	0	1	47	48	0	0	47	48	0	1	47	48

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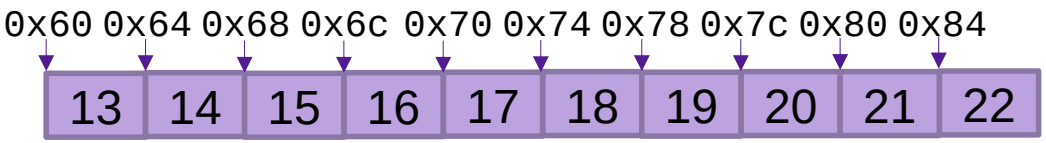
Memory



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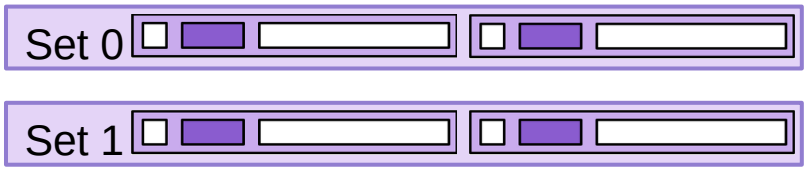

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rd 0x64	0110=0x6	0	100	Hit	14
rd 0x60	0110=0x6	0	000	Hit	13
rd 0x80	1000=0x8	0	000	Hit	21
rd 0x70	0111=0x7	0	000	Miss	

Time

Set 0						Set 1					
Line 0			Line 1			Line 0			Line 1		
0	0	47 48	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
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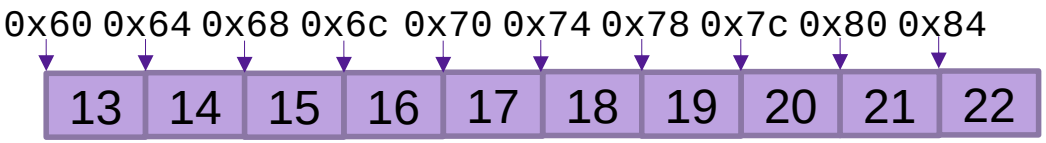

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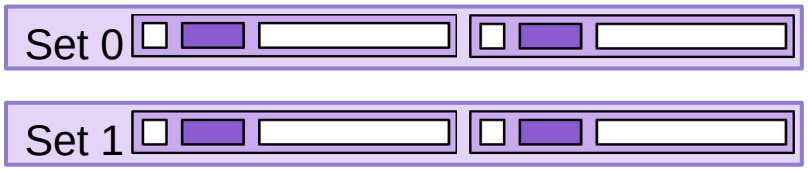

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1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	0	1	47 48	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	6	13 14	1	8	21 22	0	0	47 48	0	1	47 48
1	7	17 18	1	8	21 22	0	0	47 48	0	1	47 48

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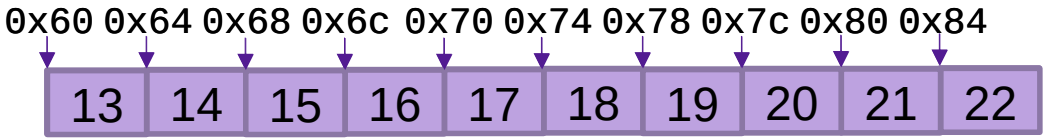
  - Write-through + No-write-allocate
  - Write-back + Write-allocate

Exercise: Write-back + Write-allocate

Memory



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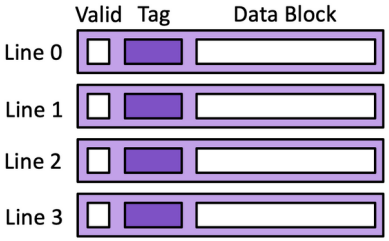

Assume 8 byte data blocks (fit 2 ints)

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rd 0x74					
wr 8,0x70					
wr 9,0x64					
rd 0x64					
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Line 0			Line 1			Line 2			Line 3			W
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54	

Exercise: Write-back + Write-allocate

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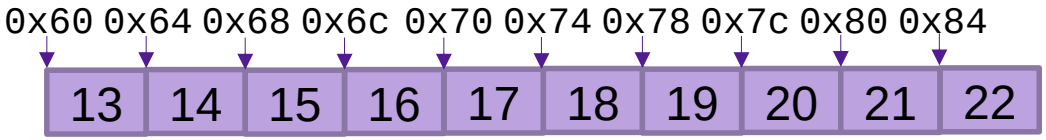

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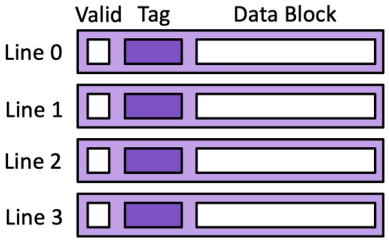

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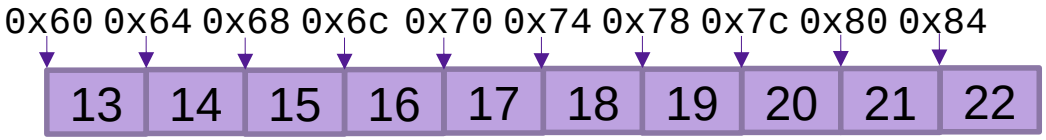

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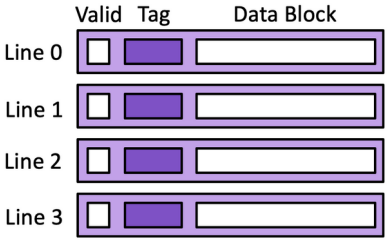

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rd 0x74	011	10	100		
wr 8,0x70					
wr 9,0x64					
rd 0x64					
rd 0x80					

Line 0			Line 1			Line 2			Line 3			W
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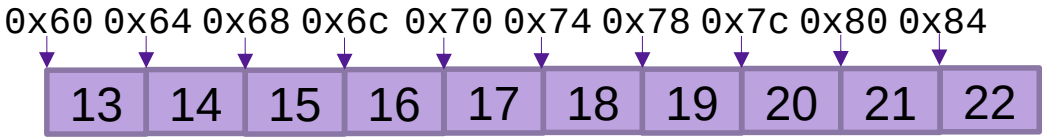

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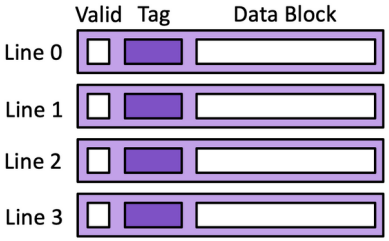

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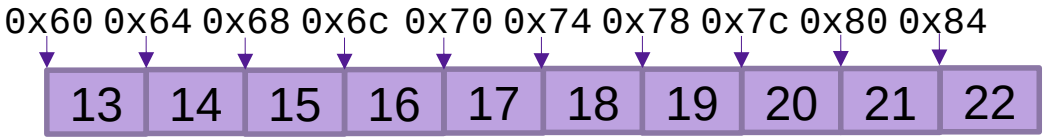

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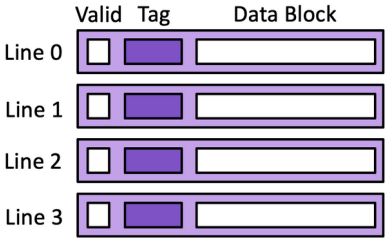

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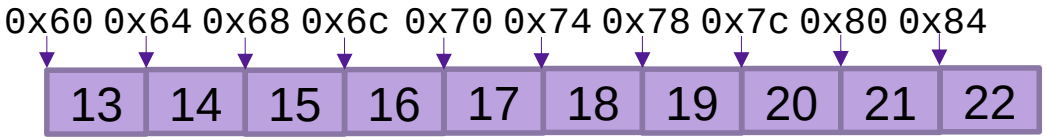

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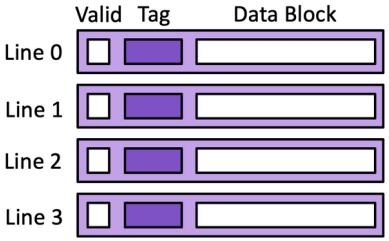

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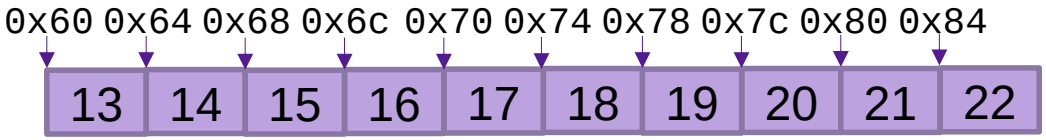

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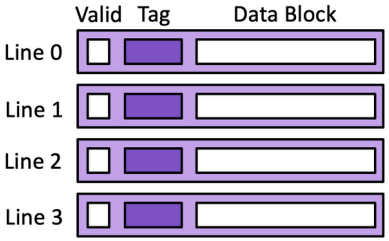

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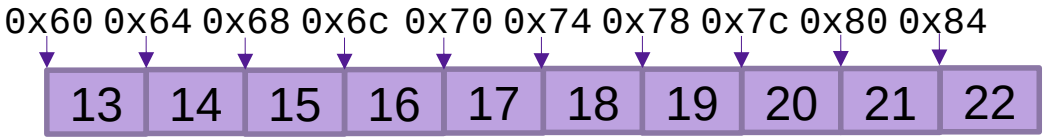

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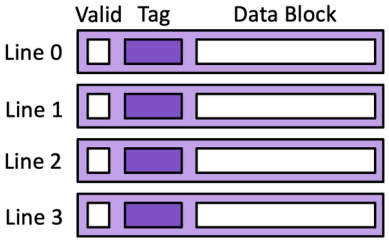

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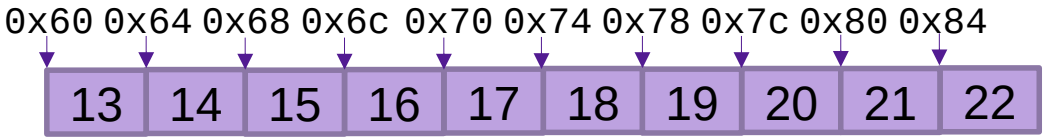

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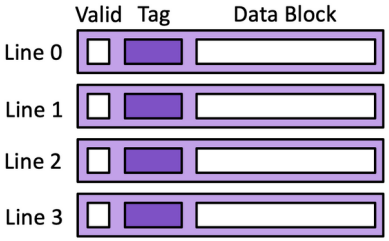

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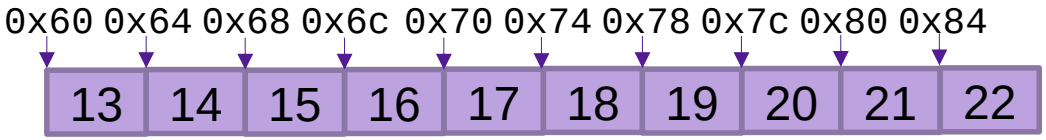

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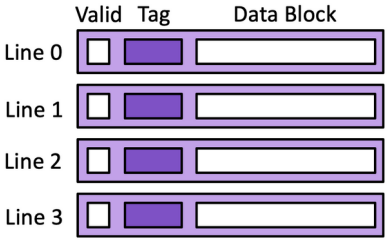

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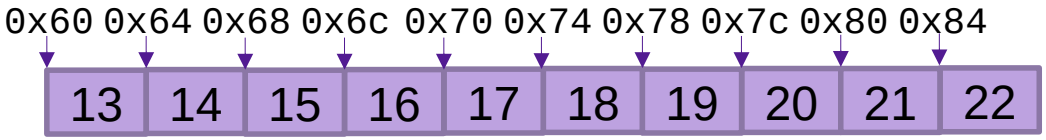

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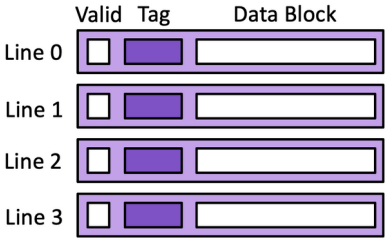

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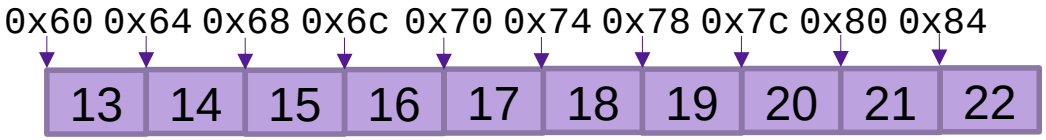

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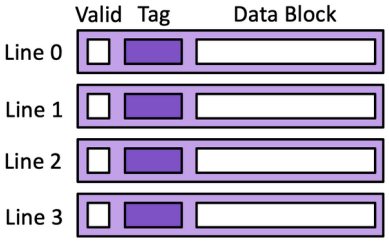

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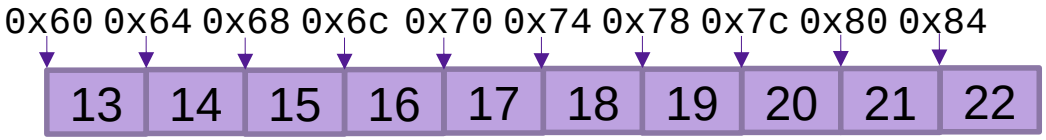

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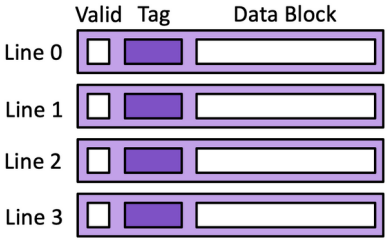

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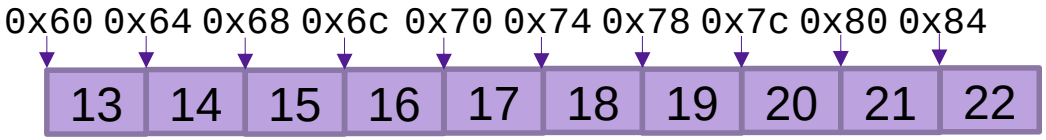

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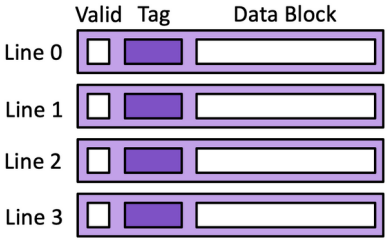

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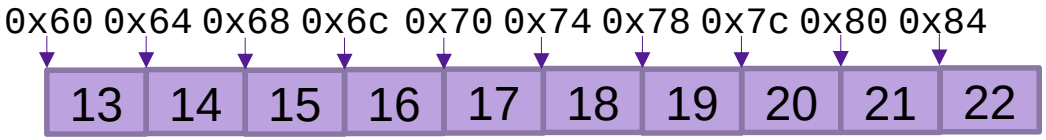

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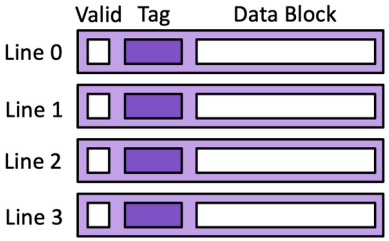

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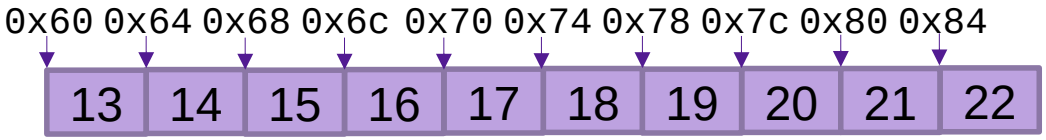

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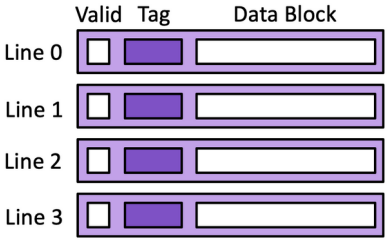

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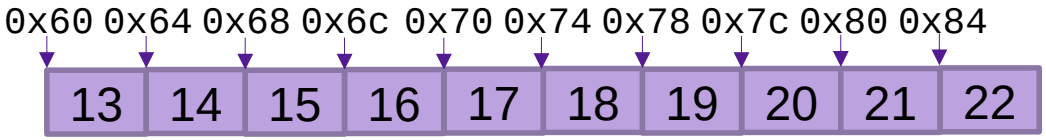
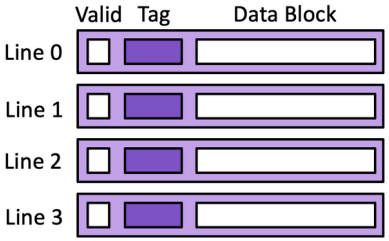
0	0	47	48	0	8	49	50	1	3	17	18	0	1	53	54	N
0	0	47	48	0	8	49	50	1	3	8	18	0	1	53	54	N
1	3	13	9	0	8	49	50	1	3	8	18	0	1	53	54	N

Exercise: Write-back + Write-allocate

Memory



Cache



Assume 8 byte data blocks (fit 2 ints)

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wr 8,0x70	011	10	000	h	
wr 9,0x64	011	00	100	m	
rd 0x64	011	00	100	h	
rd 0x80					

Line 0			Line 1			Line 2			Line 3			W
0	0	47 48	0	8	49 50	0	a	51 52	0	1	53 54	
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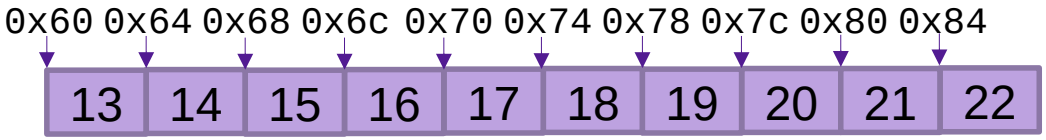

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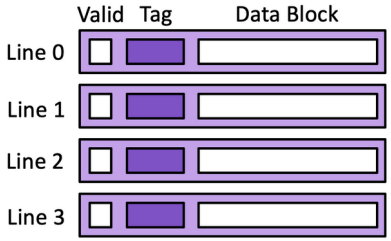

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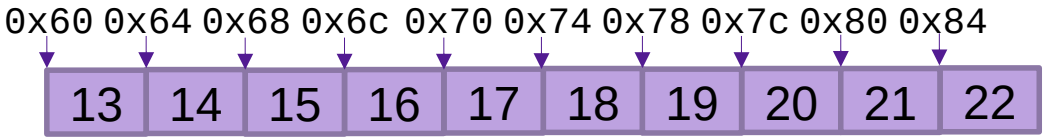

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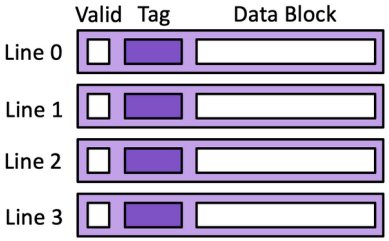

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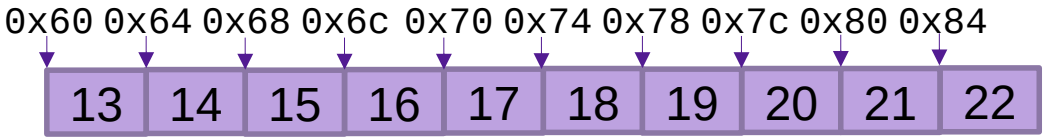

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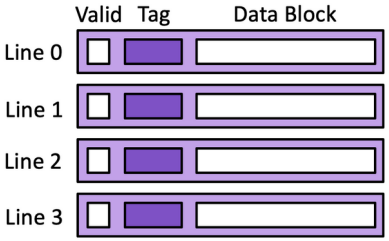

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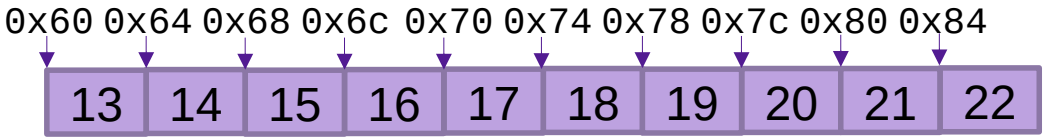

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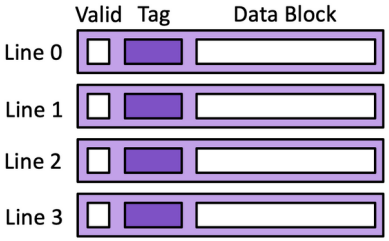

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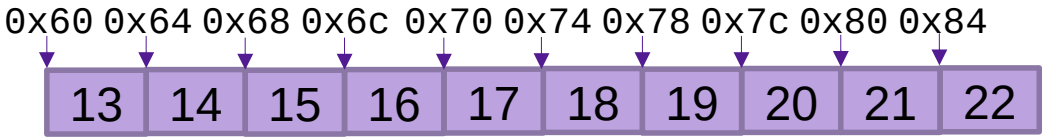

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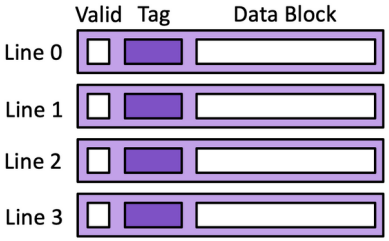

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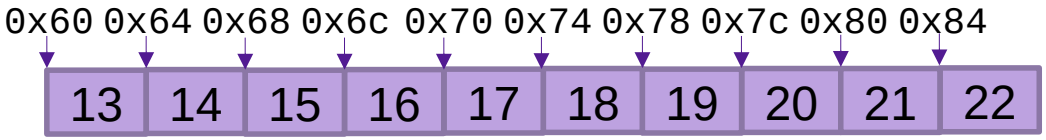

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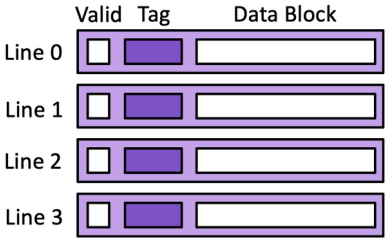

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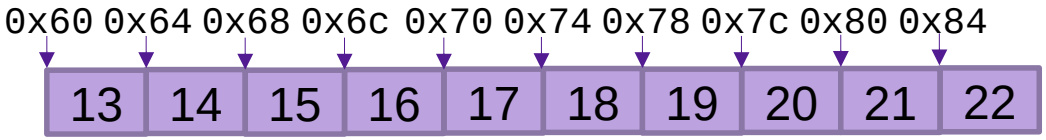

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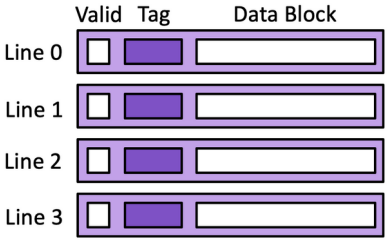

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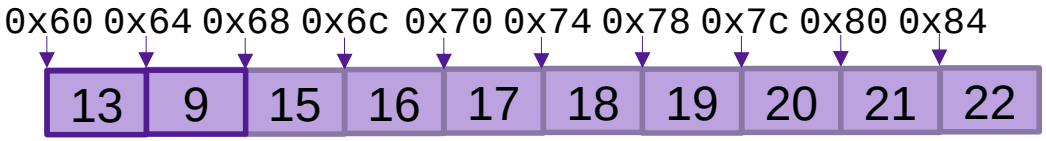
Exercise: Write-back + Write-allocate

Memory



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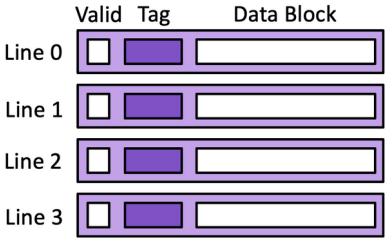

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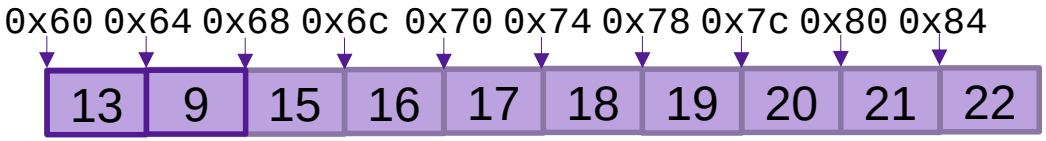

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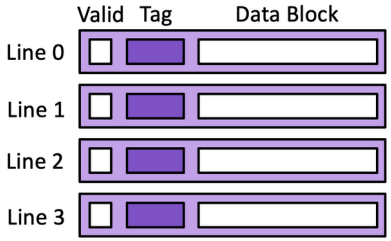

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1	3	13 9 D	0	8	49 50	1	3	8 18 D	0	1	53 54	N
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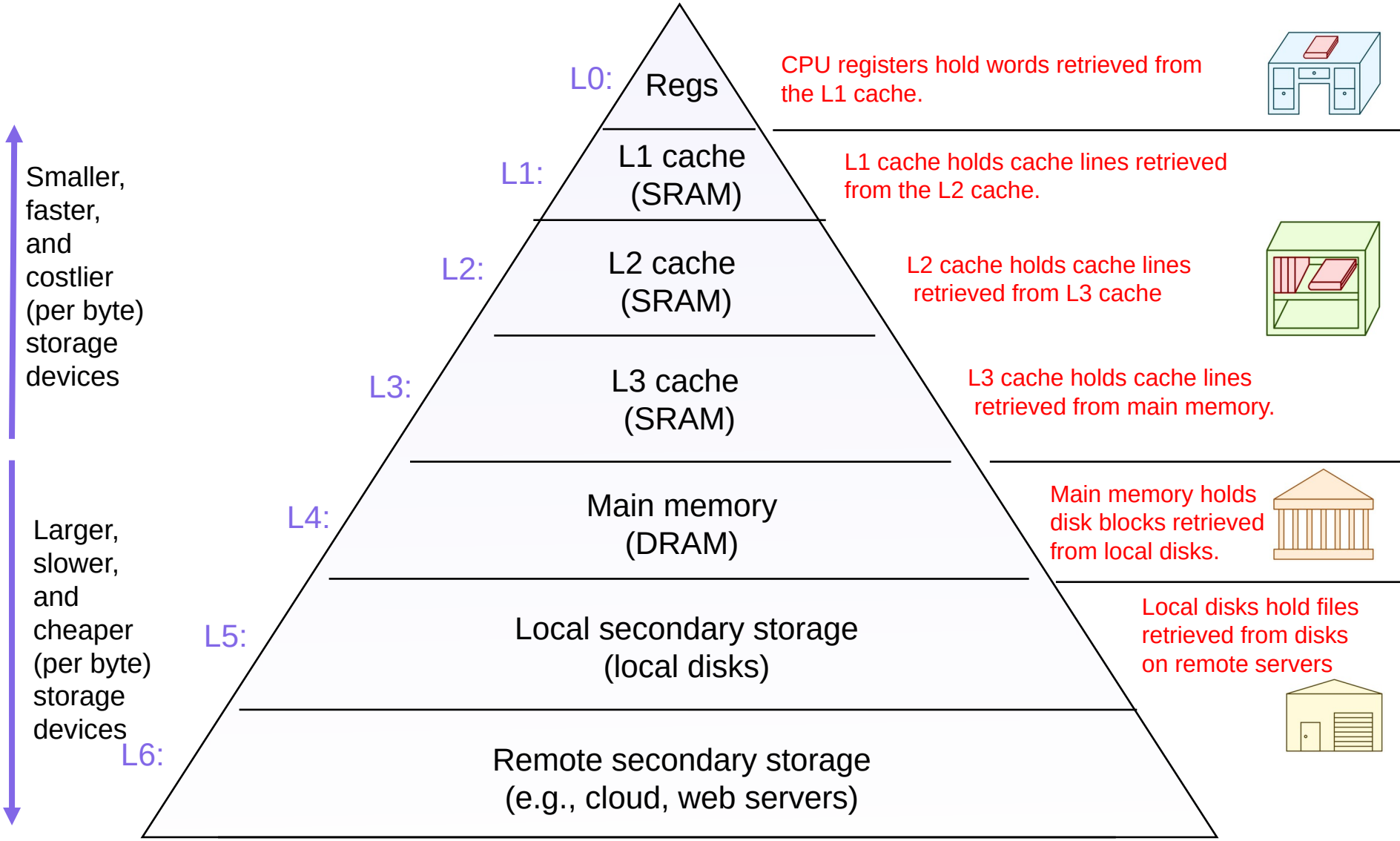
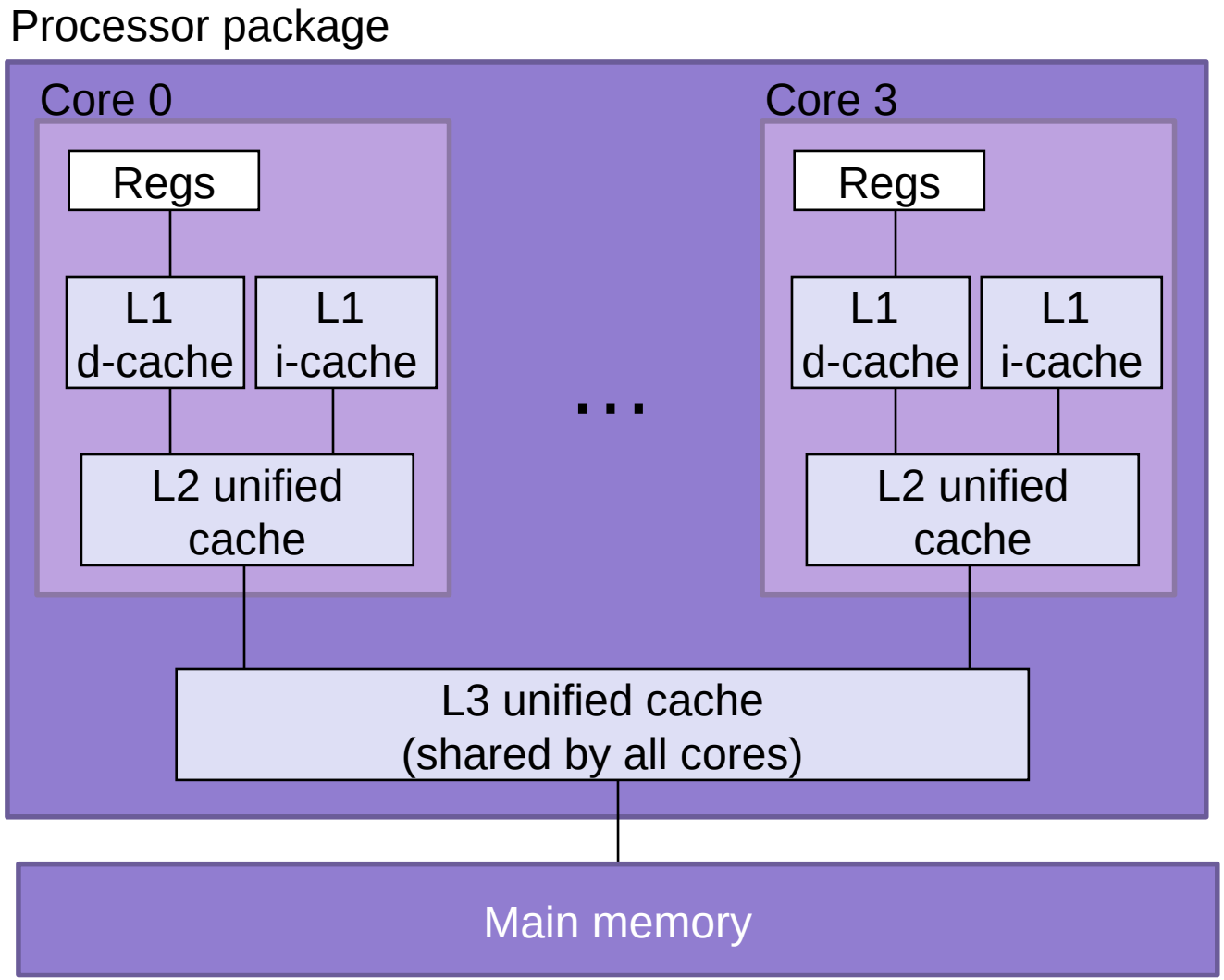
Caching Organization Summarized

- A cache consists of lines
- A **line** contains
  - A **block** of bytes, the data values from memory
  - A **tag**, indicating where in memory the values are from
  - A **valid bit**, indicating if the data are valid
- Lines are organized into sets
  - **Direct-mapped cache:** one line per set
  - **k-way associative cache:** k lines per set
  - **Fully associative cache:** all lines in one set
- Caches handle both reads and writes
  - **write-through:** write to both cache and memory
  - **write-back:** write only to cache, write to memory on evict,
  - **write-allocate:** alloc on any miss
  - **no-write allocate:** alloc only on read miss

Memory Hierarchy



Typical Intel Core i7 Hierarchy



L1 d-cache and i-cache:
32 KB, 8-way
Access: 4 cycles

L2 unified cache:
256 KB, 8-way
Access: 10 cycles

L3 unified cache:
8 MB, 16-way
Access: 40-75 cycles

Block size: 64 bytes for
caches.