

Direct Mapped Cache (Note: cache line byte offsets are reversed from the text: text is left to right)

7 bit addresses = $2^7 = 128$ bytes addressable memory

4 byte blocks - 2 bits for block offset and 32 blocks of addressable memory

2 set bits = $2^2 = 4$ sets of cache

3 remaining tag bits are used to determine which of $2^3 = 8$ possible blocks are in each of the 4 cache sets:

Set 0: Blocks 0, 4, 8, 12, 16, 20, 24, 28

Set 1: Blocks 1, 5, 9, 13, 17, 21, 25, 29

Set 2: Blocks 2, 6, 10, 14, 18, 22, 26, 30

Set 3: Blocks 3, 7, 11, 15, 19, 23, 27, 31

Tag Values: 0, 1, 2, 3, 4, 5, 6, 7

if bytes 14, 20, 29 were in cache, where would they be?

Cache:

overhead (+ valid + dirty bits)

| D V | | Set | Tag | HI | Data: 4 Byte Blocks | | Byte 14 | Byte 20 | Byte 29 |
|-----|---|-----|-----|----|---------------------|----|---------|---------|---------|
| | | 00 | 000 | | 10 | 01 | 00 | | |
| 0 | 1 | 01 | 000 | | | | | | |
| | | 10 | 000 | | | | | | |
| 0 | 1 | 11 | 001 | | | | | | |

→ This arrangement allows for contiguous blocks to be in cache at same time, but does not allow for arbitrary combinations of blocks in cache at same time. (Examples of tag values for various contiguous blocks should be given: 0, 1, 2, 3 + 23, 4, 5)

Block #

| Decimal Addr | Tag | Tag | Tag | Set | Set | Offset | Offset |
|--------------|-----|-----|-----|-----|-----|--------|--------|
|--------------|-----|-----|-----|-----|-----|--------|--------|

Direct Mapped
Example

Block 0

Block 1

Block 2

Block 3

Block 4

Block 5

Block 6

Block 7

Block 8

Block 9



| Decimal Addr | Tag | Tag | Tag | Set | Set | Offset | Offset |
|--------------|-----|-----|-----|-----|-----|--------|--------|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 4 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 6 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| 8 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 10 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 11 | 0 | 0 | 0 | 1 | 0 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 13 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 14 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 15 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| 16 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 18 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 19 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| 20 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| 21 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| 22 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |
| 23 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| 24 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 25 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| 26 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| 27 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 28 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| 29 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| 30 | 0 | 0 | 1 | 1 | 1 | 1 | 0 |
| 31 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 32 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 33 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 34 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 35 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 36 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| 37 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |

(a variant w/ 3 set bits +
2 tag bits)

- | | | |
|---------|--------|---------------|
| Set 0 : | Blocks | 0, 8, 16, 24, |
| Set 1 : | Blocks | 1, 9, 17, 25 |
| Set 2 : | Blocks | 2, 11, 18, 26 |
| Set 3 : | Blocks | 3, 12, 19, 27 |
| Set 4 : | Blocks | 4, 13, 20, 28 |
| Set 5 : | Blocks | 5, 14, 21, 29 |
| Set 6 : | Blocks | 6, 15, 22, 30 |
| Set 7 : | Blocks | 7, 16, 23, 31 |
| | | <hr/> |
| | | 0 1 2 3 |

set 7: 1210
cache : Tags Values: 0 1 2 3

4 byte blocks

| Set | tag | | | |
|-----|-----|--|--|--|
| 000 | | | | |
| 001 | | | | |
| 010 | | | | |
| 011 | | | | |
| 100 | | | | |
| 101 | | | | |
| 110 | | | | |
| 111 | | | | |

Direct-Mapped
Example B

| Decimal Addr | Tag | Tag | Tag Set | Set | Set | Offset | Offset |
|--------------|-----|-----|--------------------|-----|-----|--------|--------|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 4 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 6 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| 8 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 10 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 11 | 0 | 0 | 0 | 1 | 0 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 13 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 14 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 15 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| 16 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 18 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 19 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| 20 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| 21 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| 22 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |
| 23 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| 24 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 25 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| 26 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| 27 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 28 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| 29 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| 30 | 0 | 0 | 1 | 1 | 1 | 1 | 0 |
| 31 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 32 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 33 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 34 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 35 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 36 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| 37 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |

Block 0

Block 1

Block 2

Block 3

Block 4

Block 5

Block 6

Block 7

Block 8

Block 9

;

Set-Associative

EXAMPLE: 2-way Set-associative

Block Present

| set | D | V | tag | 00 | 01 | 10 | 11 | |
|-----|---|---|-------|----|----|----|----|---|
| 0/0 | | 1 | 0 1 0 | | X | | | 8 |
| | | 1 | 0 0 1 | | | | | 4 |
| 0/1 | | 1 | 0 0 1 | | | | | 5 |
| | | 0 | | | | | | |
| 1/0 | | 1 | 0 0 1 | | | | | 6 |
| | | 1 | 0 0 0 | | | | | 2 |
| 1/1 | | 1 | 0 0 1 | | | | X | 7 |
| | | 1 | 0 0 0 | | | | | 3 |

lookup: $\underbrace{010}_{\text{tag}} \underbrace{00}_{\text{set}} / \underbrace{01}_{\text{offset}}$ yes!

lookup: $\underbrace{001}_{\text{tag}} \underbrace{11}_{\text{set}} / \underbrace{11}_{\text{offset}}$ yes!

lookup: $\underbrace{010}_{\text{tag}} \underbrace{01}_{\text{set}} / \underbrace{01}_{\text{offset}}$

MISS!
So bring in to
empty line
+ set valid bit

lookup: $\underbrace{000}_{\text{tag}} \underbrace{00}_{\text{set}} / \underbrace{11}_{\text{offset}}$

MISS!
So, must replace
one of the
set 00 lines

| Decimal Addr | Tag | Tag | Tag | Set | Set | Offset | Offset |
|--------------|-----|-----|-----|-----|-----|--------|--------|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 4 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 6 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| 8 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 10 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 11 | 0 | 0 | 0 | 1 | 0 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 13 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 14 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 15 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| 16 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 18 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 19 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| 20 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| 21 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| 22 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |
| 23 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| 24 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 25 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| 26 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| 27 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 28 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| 29 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| 30 | 0 | 0 | 1 | 1 | 1 | 1 | 0 |
| 31 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 32 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 33 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 34 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 35 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 36 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| 37 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |

Set-Associative

Block 0

Block 1

Block 2

Block 3

Block 4

Block 5

Block 6

Block 7

Block 8

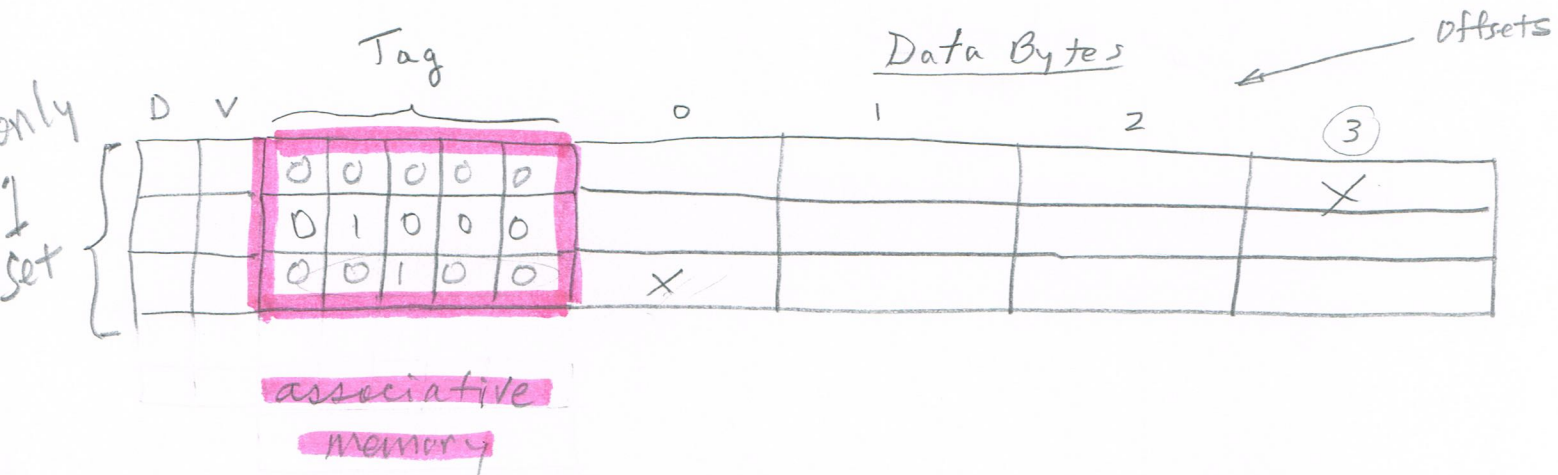
Block 9

⋮

Fully Associative Cache

11/27/2017

- only 1 set - so no bits in address for set
 - see Fully Associative Address Table
 - tag = block #, so no restriction on simultaneous blocks in cache
- Cache: can be any size + there are only offset + tag bits in address.



→ lookup: $\overbrace{00000}^{\text{Yes}} \textcircled{11}$ offset 3

→ lookup: $\overbrace{00100}^{\text{Yes}} \textcircled{00}$ offset 0

lookup: $\overbrace{00010}^{\text{No!}} \textcircled{01}$ offset 1

Cache miss! which to replace?

was not a question w/ Direct Mapped.

See 36-5

| Decimal Addr | Tag | Tag | Tag | Tag | Tag | Offset | Offset |
|--------------|-----|-----|-----|-----|-----|--------|--------|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 2 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 4 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 6 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| 8 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 10 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 11 | 0 | 0 | 0 | 1 | 0 | 1 | 1 |
| 12 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 13 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 14 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 15 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| 16 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 18 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 19 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| 20 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| 21 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| 22 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |
| 23 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| 24 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 25 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| 26 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| 27 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 28 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| 29 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| 30 | 0 | 0 | 1 | 1 | 1 | 1 | 0 |
| 31 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 32 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 33 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 34 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 35 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| 36 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| 37 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |

Fully Associative

Block 0

Block 1

Block 2

Block 3

Block 4

Block 5

Block 6

Block 7

Block 8

Block 9