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CS61C : Machine Structures

Lecture 33
Caches II

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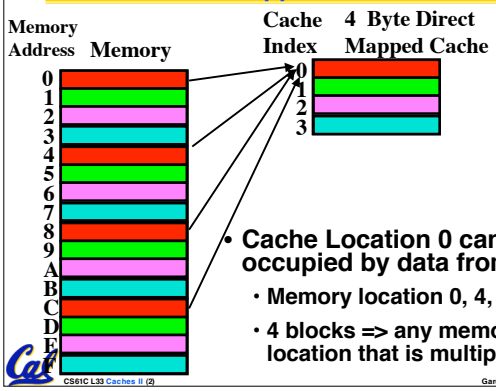
The Incredibles! ⇒

Cal wins AGAIN, upping them to 8-1 with a 42-12 victory over UW. JJ Arrington rushed for 121 yards, and has 100+ yard efforts in all 9 games this year. (The Pac-10 record is 11 by Marcus Allen when he won the Heisman.) The Big Game is next Sat; we're 4th in ALL polls!

calbears.collegesports.com/sports/m-footbl/recaps/111304aaa.html

Review: Direct-Mapped Cache



- Cache Location 0 can be occupied by data from:
  - Memory location 0, 4, 8, ...
  - 4 blocks => any memory location that is multiple of 4

Issues with Direct-Mapped

Tag | Index | Offset

- Since multiple memory addresses map to same cache index, how do we tell which one is in there?
- What if we have a block size > 1 byte?
- Answer: divide memory address into three fields

	HEIGHT	WIDTH
tttttttttttttttt	iiiiiiiii	oooo
tag to check if have correct block	index to select block	byte offset within block

Direct-Mapped Cache Terminology

- All fields are read as unsigned integers.
- Index: specifies the cache index (which "row" of the cache we should look in)
- Offset: once we've found correct block, specifies which byte within the block we want -- I.e., which "column"
- Tag: the remaining bits after offset and index are determined; these are used to distinguish between all the memory addresses that map to the same location

Direct-Mapped Cache Example (1/3)

- Suppose we have a 16KB of data in a direct-mapped cache with 4 word blocks
- Determine the size of the tag, index and offset fields if we're using a 32-bit architecture
- Offset
  - need to specify correct byte within a block
  - block contains 4 words
    - = 16 bytes
    - = 2^4 bytes
  - need 4 bits to specify correct byte

Direct-Mapped Cache Example (2/3)

- Index: (~index into an "array of blocks")
  - need to specify correct row in cache
  - cache contains 16 KB = 2^{14} bytes
  - block contains 2^4 bytes (4 words)
  - # blocks/cache
    - = $\frac{\text{bytes/cache}}{\text{bytes/block}}$
    - = $\frac{2^{14}\text{ bytes/cache}}{2^4\text{ bytes/block}}$
    - = 2^{10} blocks/cache
  - need 10 bits to specify this many rows

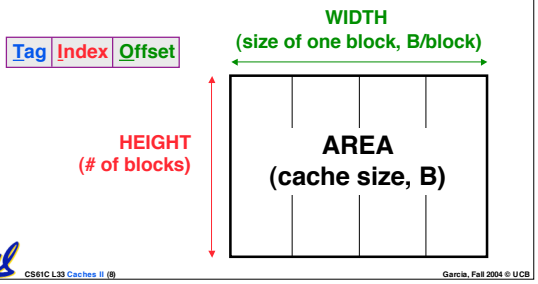
Direct-Mapped Cache Example (3/3)

- Tag: use remaining bits as tag
  - tag length = addr length - offset - index
    = 32 - 4 - 10 bits
    = 18 bits
  - so tag is leftmost 18 bits of memory address
- Why not full 32 bit address as tag?
  - All bytes within block need same address (4b)
  - Index must be same for every address within a block, so its redundant in tag check, thus can leave off to save memory (10 bits in this example)

TIO Dan's great cache mnemonic

AREA (cache size, B)
= HEIGHT (# of blocks)
* WIDTH (size of one block, B/block)

$2^{(H+W)} = 2^H * 2^W$



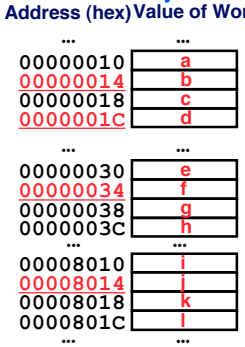
Caching Terminology

- When we try to read memory, 3 things can happen:

1. cache hit: cache block is valid and contains proper address, so read desired word
2. cache miss: nothing in cache in appropriate block, so fetch from memory
3. cache miss, block replacement: wrong data is in cache at appropriate block, so discard it and fetch desired data from memory (cache always copy)

Accessing data in a direct mapped cache

- Ex.: 16KB of data, direct-mapped, 4 word blocks
- Read 4 addresses
  1. 0x00000014
  2. 0x0000001C
  3. 0x00000034
  4. 0x00008014
- Memory values on right:
  - only cache/ memory level of hierarchy



Accessing data in a direct mapped cache

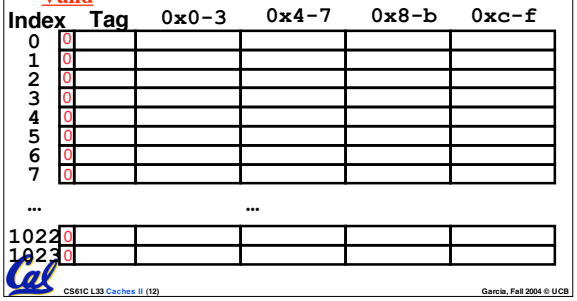
- 4 Addresses:
  - 0x00000014, 0x0000001C, 0x00000034, 0x00008014
- 4 Addresses divided (for convenience) into Tag, Index, Byte Offset fields

```
00000000000000000 0000000001 0100
00000000000000000 0000000001 1100
00000000000000000 0000000011 0100
00000000000000010 0000000001 0100
```

Tag Index Offset

16 KB Direct Mapped Cache, 16B blocks

- Valid bit: determines whether anything is stored in that row (when computer initially turned on, all entries invalid)



1. Read 0x00000014

• 00000000000000000000 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	0					
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

So we read block 1 (0000000001)

• 00000000000000000000 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	0					
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

No valid data

• 00000000000000000000 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	0					
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

So load that data into cache, setting tag, valid

• 00000000000000000000 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

Read from cache at offset, return word b

• 00000000000000000000 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

2. Read 0x0000001C = 0…00 0..001 1100

• 00000000000000000000 0000000001 1100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

Index is Valid

• 000000000000000000 0000000001 1100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

Index valid, Tag Matches

• 000000000000000000 0000000001 1100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

Index Valid, Tag Matches, return d

• 000000000000000000 0000000001 1100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

3. Read 0x00000034 = 0…00 0..011 0100

• 000000000000000000 0000000011 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

So read block 3

• 000000000000000000 0000000011 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

No valid data

• 000000000000000000 0000000011 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	0					
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

Load that cache block, return word f

- 00000000000000000000 0000000011 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	1	0	e	f	g	h
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

4. Read 0x00008014 = 0…10 0..001 0100

- 00000000000000000010 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	1	0	e	f	g	h
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

So read Cache Block 1, Data is Valid

- 00000000000000000010 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	1	0	e	f	g	h
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

Cache Block 1 Tag does not match (0 != 2)

- 00000000000000000010 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	0	a	b	c	d
2	0					
3	1	0	e	f	g	h
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

Miss, so replace block 1 with new data & tag

- 00000000000000000010 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	2	i	j	k	l
2	0					
3	1	0	e	f	g	h
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

And return word j

- 00000000000000000010 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	2	i	j	k	l
2	0					
3	1	0	e	f	g	h
4	0					
5	0					
6	0					
7	0					
...				...		
1022	0					
1023	0					

Do an example yourself. What happens?

- Chose from: Cache: Hit, Miss, Miss w. replace
  Values returned: a ,b, c, d, e, ..., k, l
- Read address 0x00000030 ?
  00000000000000000000 0000000011 0000
- Read address 0x0000001c ?
  00000000000000000000 0000000001 1100

Cache

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0	0					
1	1	2	i	j	k	l
2	0					
3	1	0	e	f	g	h
4	0					
5	0					
6	0					
7	0					
...				...		

Administrivia

Answers

- 0x00000030 a hit
  Index = 3, Tag matches, Offset = 0, value = e
- 0x0000001c a miss
  Index = 1, Tag mismatch, so replace from memory, Offset = 0xc, value = d
- Since reads, values must = memory values whether or not cached:
  - 0x00000030 = e
  - 0x0000001c = d

Memory

Address	Value of Word
...	...
00000010	a
00000014	b
00000018	c
0000001c	d
...	...
00000030	e
00000034	f
00000038	g
0000003c	h
...	...
00008010	i
00008014	j
00008018	k
0000801c	l
...	...

Peer Instruction

A. Mem hierarchies were invented before 1950. (UNIVAC I wasn't delivered 'til 1951)

B. If you know your computer's cache size, you can often make your code run faster.

C. Memory hierarchies take advantage of spatial locality by keeping the most recent data items closer to the processor.

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Peer Instructions

1. All caches take advantage of spatial locality.
2. All caches take advantage of temporal locality.
3. On a read, the return value will depend on what is in the cache.

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

And in Conclusion…

- Mechanism for transparent movement of data among levels of a storage hierarchy
  - set of address/value bindings
  - address ⇒ index to set of candidates
  - compare desired address with tag
  - service hit or miss
    - load new block and binding on miss

address: tag index offset
00000000000000000000 0000000001 1100

Index	Valid	Tag	0x0-3	0x4-7	0x8-b	0xc-f
0						
1	1	0	a	b	c	d
2						
3						