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UCB CS61C : Machine Structures

Lecture 13 – Caches II
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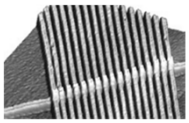
MEMRISTOR MEMORY ON ITS WAY (HOPEFULLY)

HP has begun testing research prototypes of a novel non-volatile memory element, the memristor. They have double the storage density of flash, and has 10x more read-write cycles than flash (10^6 vs 10^5). Memristors are (in principle) also capable of being memory and logic, how cool is that? Originally slated to be ready by 2013, HP later pushed that date to some time 2014.



www.technologyreview.com/computing/25018
http://www.technologyreview.com/view/512361/can-hp-save-itself/

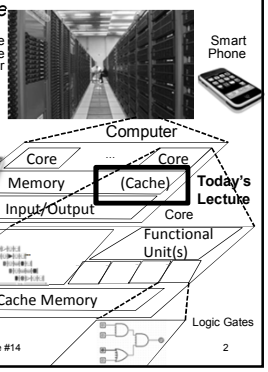
Review: New-School Machine Structures

Software

- Parallel Requests
  Assigned to computer
  e.g., Search "Katz"
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Add of 4 pairs of words
- Hardware descriptions
  All gates @ one time
- Programming Languages

Harness Parallelism & Achieve High Performance

Hardware



Review: Direct-Mapped Cache

- All fields are read as unsigned integers.
- Index
  - specifies the cache index (or "row"/block)
- Tag
  - distinguishes betw the addresses that map to the same location
- Offset
  - specifies which byte within the block we want

ttttttttttttttttt	iiiiiiiii	oooo
tag to check if have correct block	index to select block	byte offset within block

TIO Dan's great cache mnemonic

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

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

Tag	Index	Offset

Addr size (often 32 bits)

WIDTH (size of one block, B/block)

HEIGHT (# of blocks)

AREA (cache size, B)

Memory Access without Cache

- Load word instruction: lw $t0, 0($t1)
- $t1 contains 1022_{ten}, Memory[1022] = 99

1. Processor issues address 1022_{ten} to Memory
2. Memory reads word at address 1022_{ten} (99)
3. Memory sends 99 to Processor
4. Processor loads 99 into register $t1

Memory Access with Cache

- Load word instruction: lw $t0, 0($t1)
- $t1 contains 1022_{ten}, Memory[1022] = 99
- With cache (similar to a hash)
  1. Processor issues address 1022_{ten} to Cache
  2. Cache checks to see if has copy of data at address 1022_{ten}
     - 2a. If finds a match (Hit): cache reads 99, sends to processor
     - 2b. No match (Miss): cache sends address 1022 to Memory
       - I. Memory reads 99 at address 1022_{ten}
       - II. Memory sends 99 to Cache
       - III. Cache replaces word with new 99
       - IV. Cache sends 99 to processor
  3. Processor loads 99 into register $t1

Caching Terminology

- When reading memory, 3 things can happen:
  - cache hit:
    cache block is valid and contains proper address, so read desired word
  - cache miss:
    nothing in cache in appropriate block, so fetch from memory
  - cache miss, block replacement:
    wrong data is in cache at appropriate block, so discard it and fetch desired data from memory (cache always copy)

Cache Terms

- Hit rate: fraction of access that hit in the cache
- Miss rate: 1 – Hit rate
- Miss penalty: time to replace a block from lower level in memory hierarchy to cache
- Hit time: time to access cache memory (including tag comparison)
- Abbreviation: "$" = cache (A Berkeley innovation!)

Accessing data in a direct mapped cache

- Ex.: 16KB of data, direct-mapped, 4 word blocks
  - Can you work out height, width, area?
- Read 4 addresses
  1. 0x00000014
  2. 0x0000001C
  3. 0x00000034
  4. 0x00008014
- Memory vals here:

Memory Address (hex)	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
...	...

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)

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

1. Read 0x00000014

- 00000000000000000 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0xc-f	0x8-b	0x4-7	0x0-3
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)

- 00000000000000000 0000000001 0100

Tag field | Index field | Offset

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

No valid data

- 00000000000000000 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0xc-f	0x8-b	0x4-7	0x0-3
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

- 00000000000000000 0000000001 0100

Tag field | Index field | Offset

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

Read from cache at offset, return word b

- 00000000000000000 0000000001 0100

Tag field | Index field | Offset

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

2. Read 0x0000001C = 0…00 0..001 1100

- 00000000000000000 0000000001 1100

Tag field | Index field | Offset

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

Index is Valid

- 00000000000000000 0000000001 1100

Tag field | Index field | Offset

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

Index valid, Tag Matches

- 00000000000000000000 0000000001 1100

Tag field | Index field | Offset

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

Index Valid, Tag Matches, return d

- 00000000000000000000 0000000001 1100

Tag field | Index field | Offset

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

3. Read 0x00000034 = 0…00 0..011 0100

- 00000000000000000000 0000000011 0100

Tag field | Index field | Offset

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

So read block 3

- 00000000000000000000 0000000011 0100

Tag field | Index field | Offset

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

No valid data

- 00000000000000000000 0000000011 0100

Tag field | Index field | Offset

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

4. Read 0x00008014 = 0…10 0..001 0100

- 00000000000000010 0000000001 0100

Tag field | Index field | Offset

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

So read Cache Block 1, Data is Valid

- 00000000000000010 0000000001 0100

Tag field | Index field | Offset

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

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

- 00000000000000010 0000000001 0100

Tag field | Index field | Offset

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

Miss, so replace block 1 with new data & tag

- 00000000000000010 0000000001 0100

Tag field | Index field | Offset

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

And return word J

- 00000000000000010 0000000001 0100

Tag field | Index field | Offset

Index	Valid	Tag	0xc-f	0x8-b	0x4-7	0x0-3
0	0					
1	1	2	l	k	j	i
2	0					
3	1	0	h	g	f	e
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 ?
  00000000000000000 0000000011 0000
- Read address 0x0000001c ?
  00000000000000000 0000000001 1100

Cache

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

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

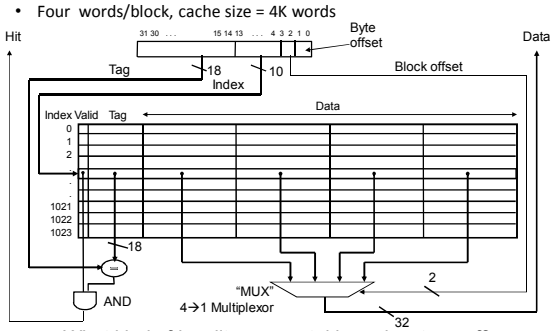
Memory Address (hex)	Value of Word
...	...
00000010	a
00000014	b
00000018	c
0000001C	d
...	...
00000030	e
00000034	f
00000038	g
0000003C	h
...	...
00008010	i
00008014	j
00008018	k
0000801C	l
...	...

Administrivia

- **Proj 1-2 due Sunday**

Multiword-Block Direct-Mapped Cache

- Four words/block, cache size = 4K words



What kind of locality are we taking advantage of?

Peer Instruction

1) **Mem hierarchies were invented before 1950. (UNIVAC I wasn't delivered 'til 1951)**
2) **All caches take advantage of spatial locality.**
3) **All caches take advantage of temporal locality.**

123
a) FFF
a) FFT
b) FTF
b) FTT
c) TFF
d) TFT
e) TTF
e) 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