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# UC Berkeley CS61C : Machine Structures

## Lecture 32 – Caches II

2007-04-09

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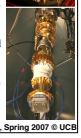
**Experts weigh in on Quantum CPU ⇒**



Most "profoundly skeptical" of the demo. D-Wave has provided almost no details of system. Scott Aaronson (Cal PhD): "it's as useful for solving problems as a roast-beef sandwich". Prof Vazirani: "they have misleaded the public by calling it a 'practical quantum computer'; no speedup over classical computers". D-Wave: It's a prototype!

technologyreview.com/Infotech/18495/



## 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 | iiiiiiiiii | 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



## 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

WIDTH
(size of one block, B/block)

HEIGHT
(# of blocks)

AREA
(cache size, B)



## 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:

| 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

```
00000000000000000000 0000000001 0100
00000000000000000000 0000000001 1100
00000000000000000000 0000000011 0100
00000000000000000010 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)

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



## 1. Read 0x00000014

- 00000000000000000000 0000000001 0100
  Tag field Index field Offset

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



## So we read block 1 (0000000001)

- 00000000000000000000 0000000001 0100
  Tag field Index field Offset

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



## No valid data

- 00000000000000000000 0000000001 0100
  Tag field Index field Offset

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



## So load that data into cache, setting tag, valid

- 00000000000000000000 0000000001 0100
  Tag field Index field Offset

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

## 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

• 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 valid, Tag Matches

• 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 Valid, Tag Matches, return d

• 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 | | | | | |





## 3. Read 0x00000034 = 0…00 0..011 0100

• 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 | 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 | 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

• 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 | 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

• 00000000000000010 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

• 00000000000000010 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 ?
00000000000000000 0000000011 0000

• Read address 0x0000001c ?
00000000000000000 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 | | | | | |
| ... | | | | ... | | |



## 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 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 |
|---|---|
| 0: | FFF |
| 1: | FFT |
| 2: | FTF |
| 3: | FTT |
| 4: | TFF |
| 5: | TFT |
| 6: | TTF |
| 7: | 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
00000000000000000 0000000001 1100

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