Caches

Han Wang
CS 3410, Spring 2012
Computer Science
Cornell University

See P&H 5.1, 5.2 (except writes)

Announcements

This week:

- PA2 Work-in-progress submission

Next six weeks:

- Two labs and two projects
- Prelim2 will be Thursday, March 29th

Agenda

- Memory Hierarchy Overview
- The Principle of Locality
- Direct-Mapped Cache
- Fully Associative Cache

Performance

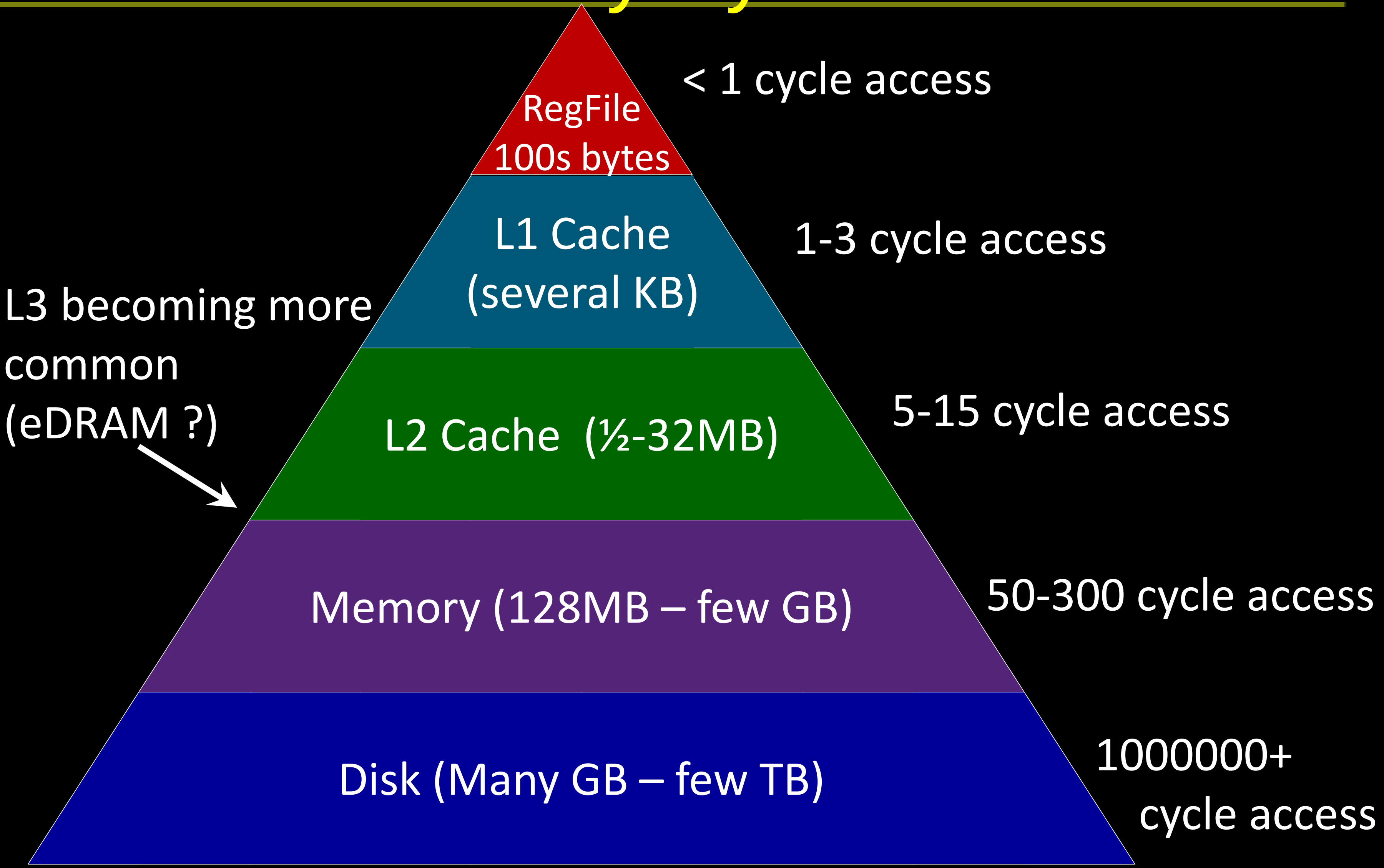
CPU clock rates ~0.2ns – 2ns (5GHz-500MHz)

Technology	Capacity	$/GB	Latency
Tape	1 TB	$.17	100s of seconds
Disk	2 TB	$.03	Millions of cycles (ms)
SSD (Flash)	128 GB	$2	Thousands of cycles (us)
DRAM	8 GB	$10	50-300 cycles (10s of ns)
SRAM off-chip	8 MB	$4000	5-15 cycles (few ns)
SRAM on-chip	256 KB	???	1-3 cycles (ns)

Others: eDRAM aka 1-T SRAM, FeRAM, CD, DVD, …

Q: Can we create illusion of cheap + large + fast?

Memory Pyramid



These are rough numbers: mileage may vary for latest/greatest
Caches usually made of SRAM (or eDRAM)

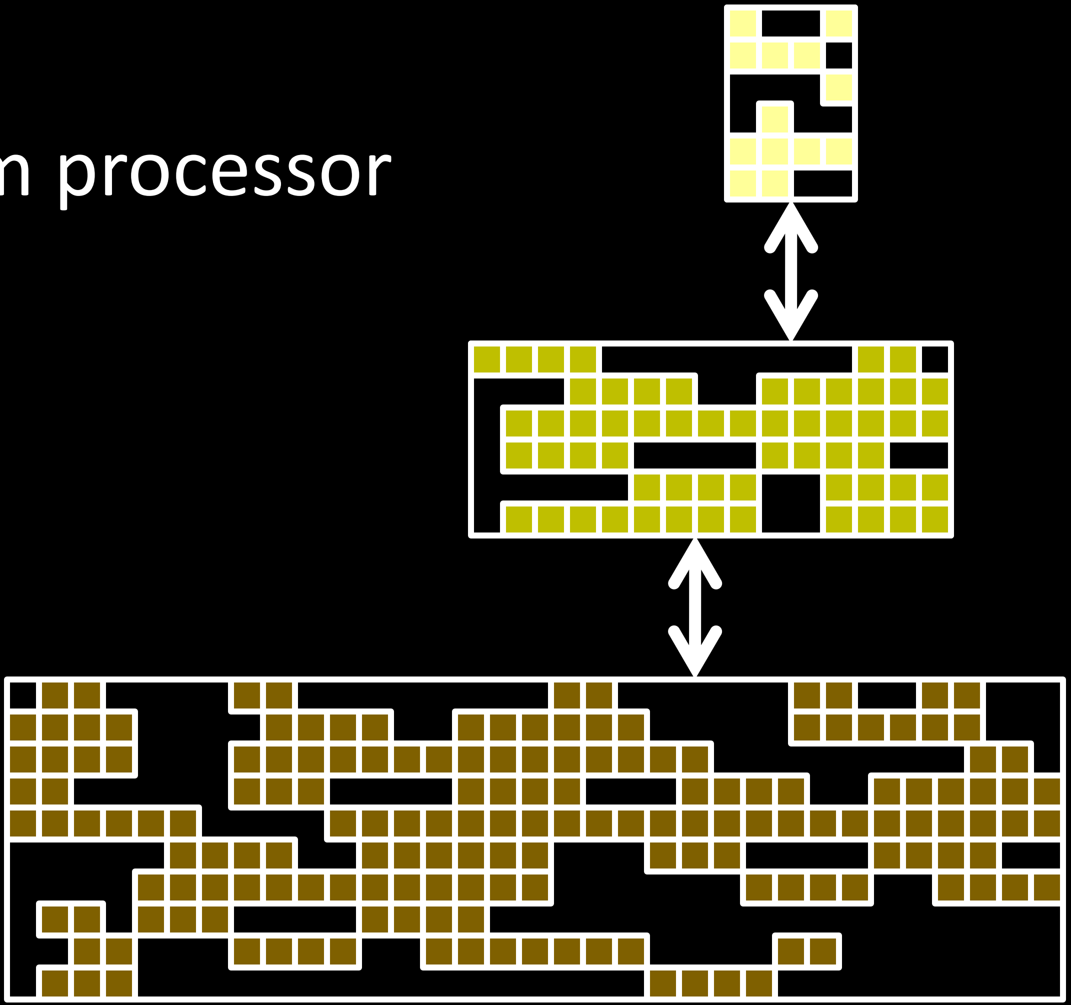
Memory Hierarchy

Memory closer to processor

- small & fast
- stores active data

Memory farther from processor

- big & slow
- stores inactive data



Active vs Inactive Data

Assumption: Most data is not active.

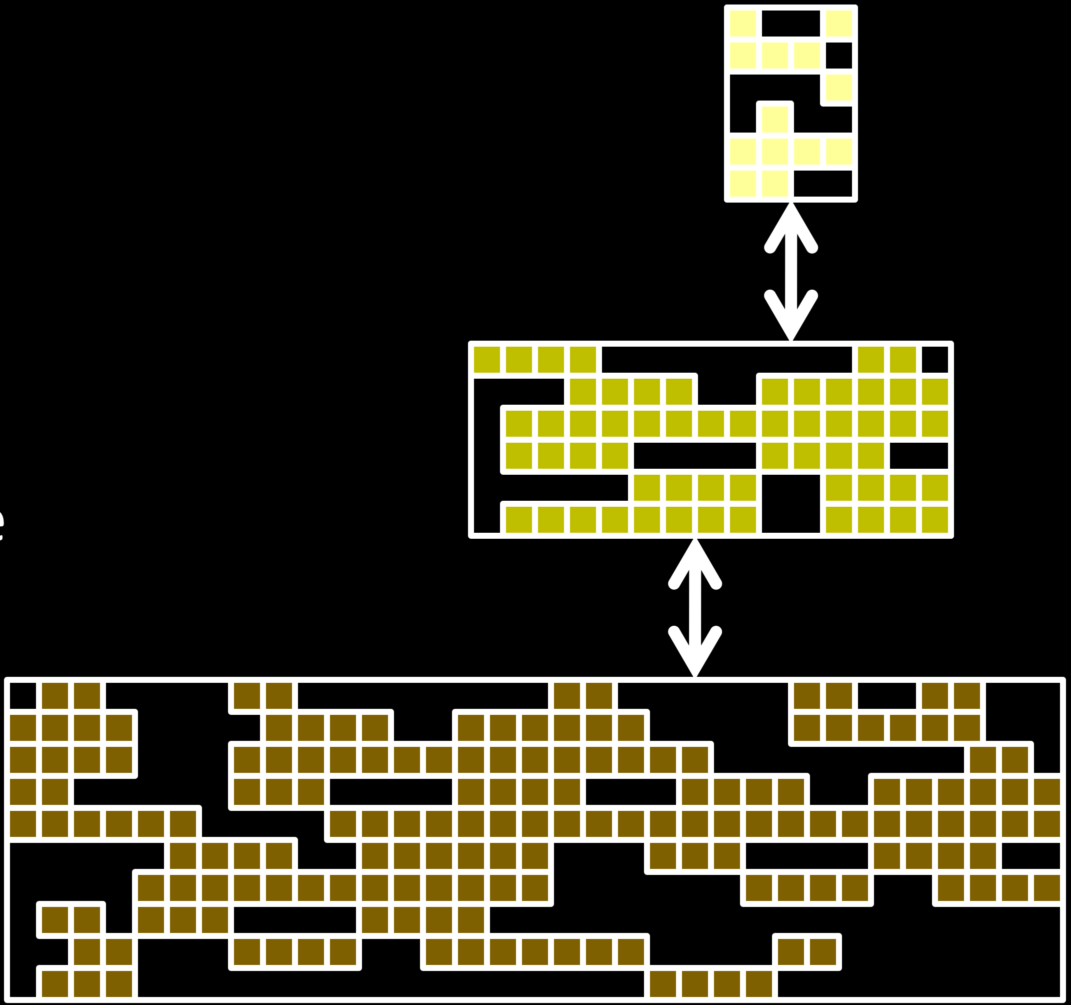
Q: How to decide what is active?

A: Programmer decides

A: Compiler decides

A: OS decides at run-time

A: Hardware decides
at run-time



Insight of Caches

Q: What is “active” data?

If Mem[x] is was accessed *recently*...

... then Mem[x] is likely to be accessed *soon*

- Exploit temporal locality:

... then Mem[$x \pm \varepsilon$] is likely to be accessed *soon*

- Exploit spatial locality:

Locality Analogy

- Writing a report on a specific topic.
- While at library, check out books and keep them on desk.
- If need more, check them out and bring to desk.
  - But don’t return earlier books since might need them
  - Limited space on desk; Which books to keep?
- You hope this collection of ~20 books on desk enough to write report, despite 20 being only 0.00002% of books in Cornell libraries

Two types of Locality

Temporal Locality (locality in time)

- If a memory location is referenced then it will tend to be referenced again soon

$\Rightarrow$ Keep most recently accessed data items closer to the processor

Spatial Locality (locality in space)

- If a memory location is referenced, the locations with nearby addresses will tend to be referenced soon

$\Rightarrow$ Move blocks consisting of contiguous words closer to the processor

Locality

Memory trace

```
0x7c9a2b18
0x7c9a2b19
0x7c9a2b1a
0x7c9a2b1b
0x7c9a2b1c
0x7c9a2b1d
0x7c9a2b1e
0x7c9a2b1f
0x7c9a2b20
0x7c9a2b21
0x7c9a2b22
0x7c9a2b23
0x7c9a2b28
0x7c9a2b2c
0x0040030c
0x00400310
0x7c9a2b04
0x00400314
0x7c9a2b00
0x00400318
0x0040031c
...
```

```
int n = 4;
int k[] = { 3, 14, 0, 10 };

int fib(int i) {
   if (i <= 2) return i;
   else return fib(i-1)+fib(i-2);
}

int main(int ac, char **av) {
   for (int i = 0; i < n; i++) {
      printi(fib(k[i]));
      prints("\n");
   }
}
```

Memory Hierarchy

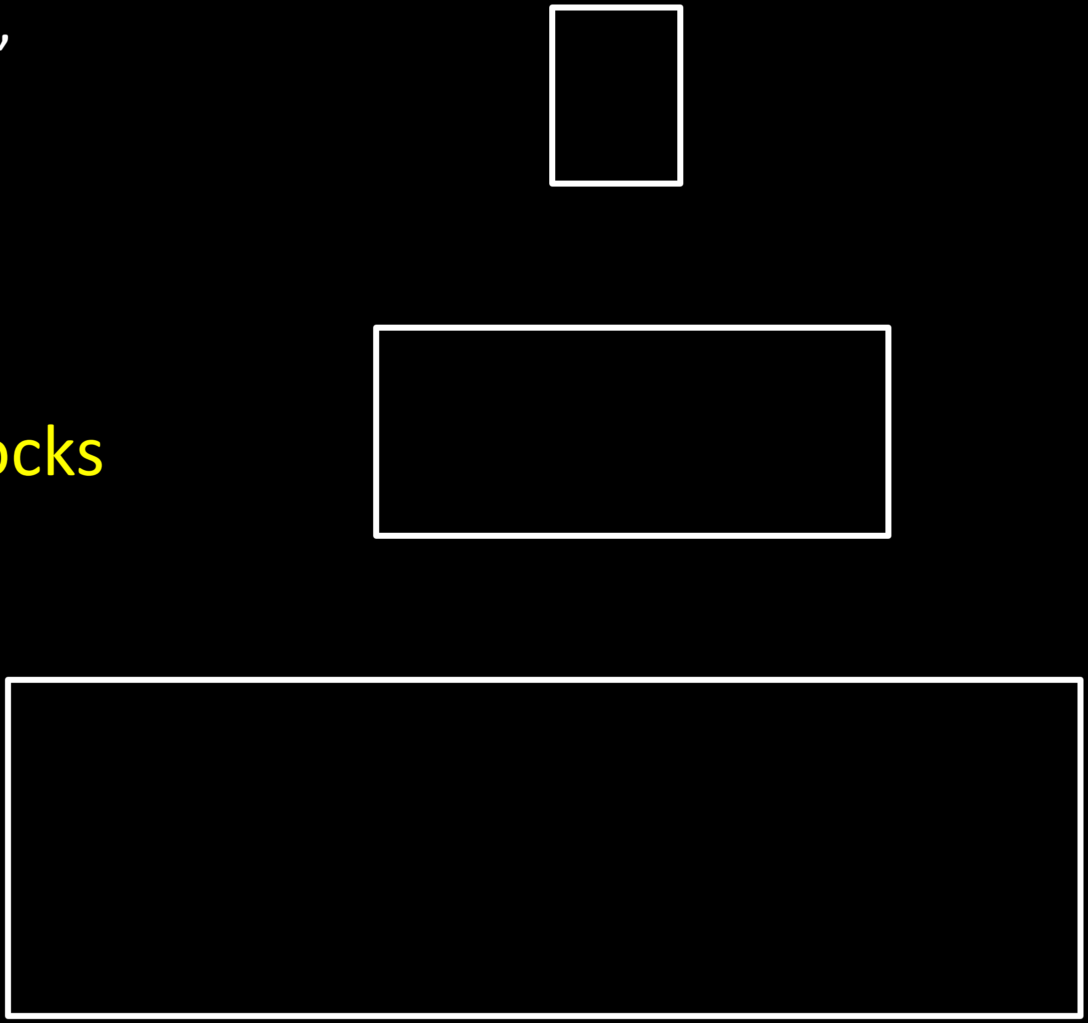
Memory closer to processor is fast but small

- usually stores subset of memory farther away
  - "strictly inclusive"
- alternatives:
  - strictly exclusive
  - mostly inclusive
- Transfer whole blocks (cache lines):

  4kb: disk ↔ ram

  256b: ram ↔ L2

  64b: L2 ↔ L1



Cache Lookups (Read)

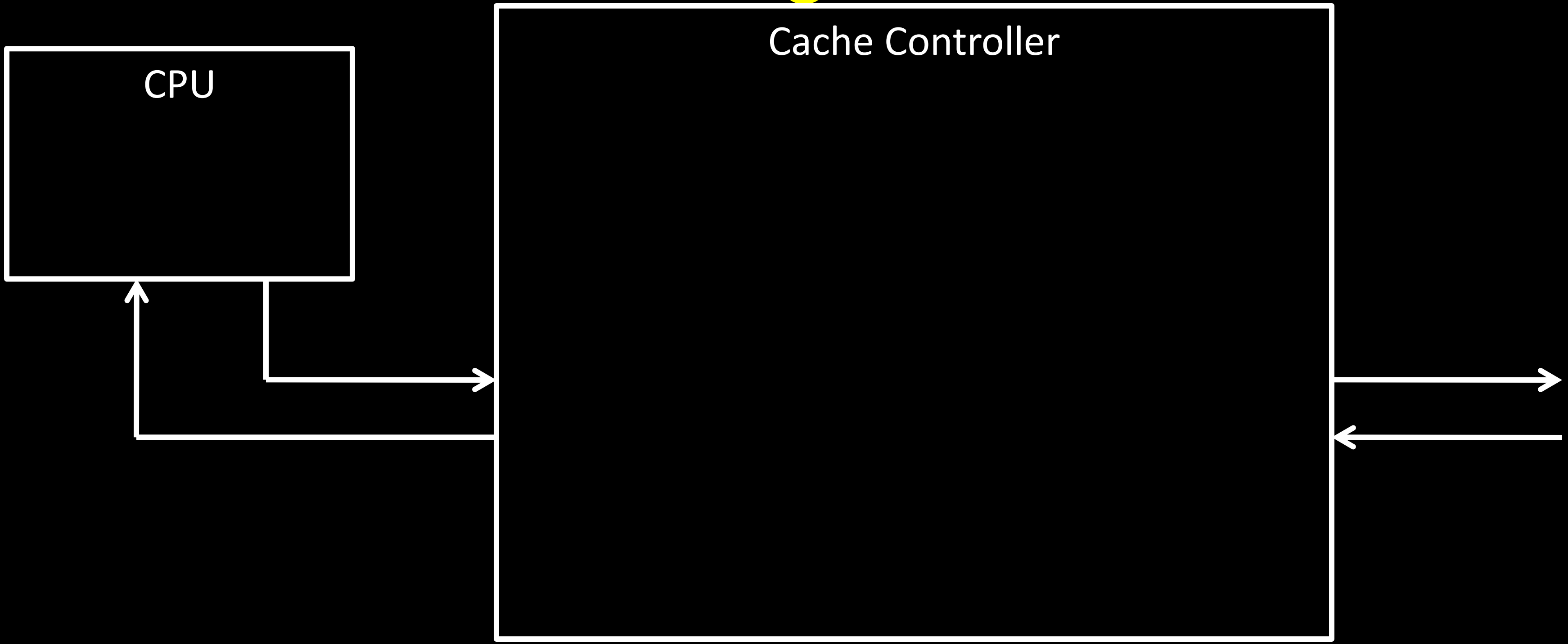
Processor tries to access Mem[x]

Check: is block containing Mem[x] in the cache?

- Yes: cache hit
  - return requested data from cache line
- No: cache miss
  - read block from memory (or lower level cache)
  - (evict an existing cache line to make room)
  - place new block in cache
  - return requested data

  → and stall the pipeline while all of this happens

Cache Organization



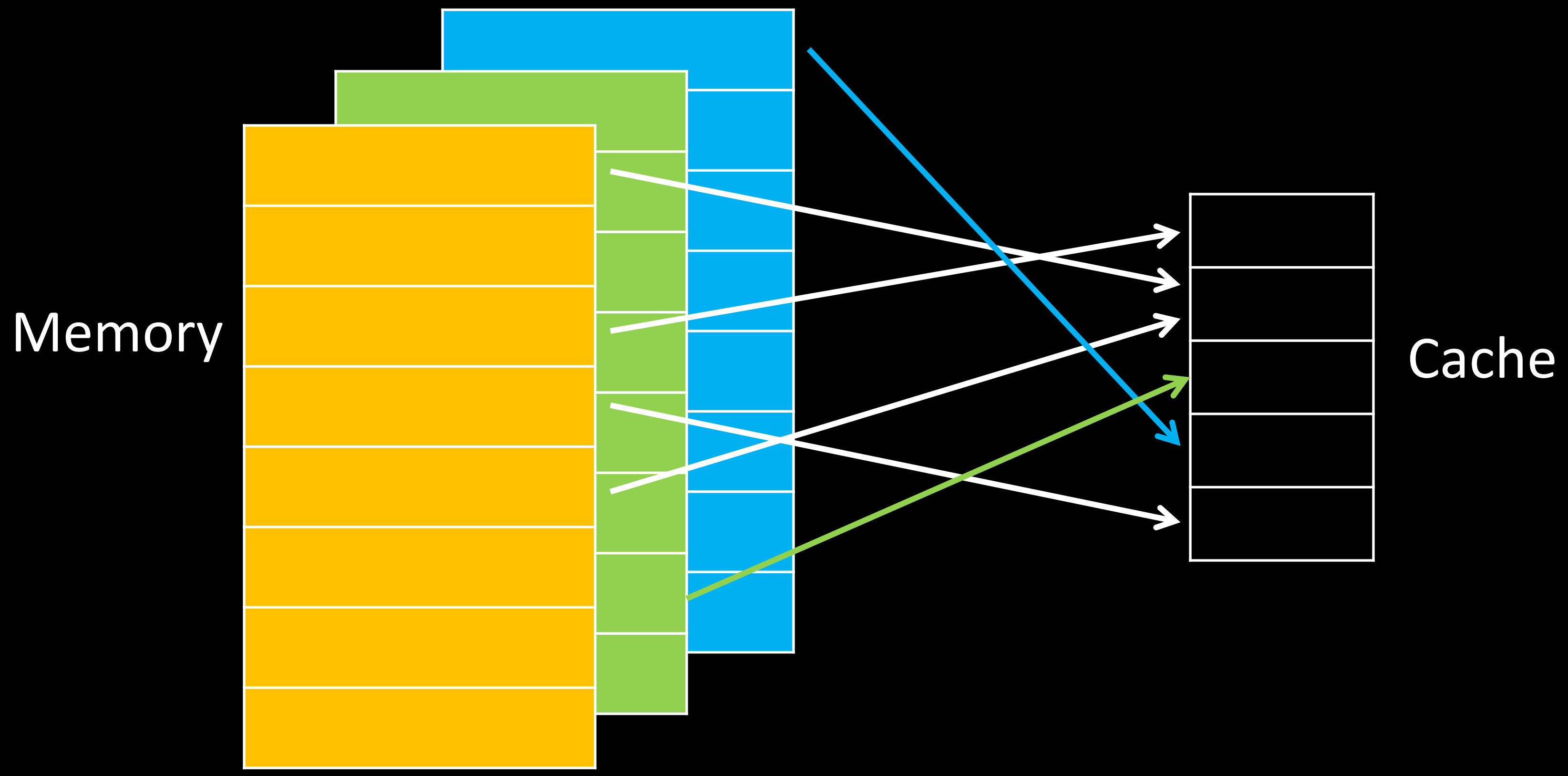
Cache has to be fast and dense

- Gain speed by performing lookups in parallel
  - but requires die real estate for lookup logic
- Reduce lookup logic by limiting where in the cache a block might be placed
  - but might reduce cache effectiveness

Three common designs

A given data block can be placed…

- … in any cache line → $\boxed{\text{Fully Associative}}$
- … in exactly one cache line → Direct Mapped
- … in a small set of cache lines → Set Associative



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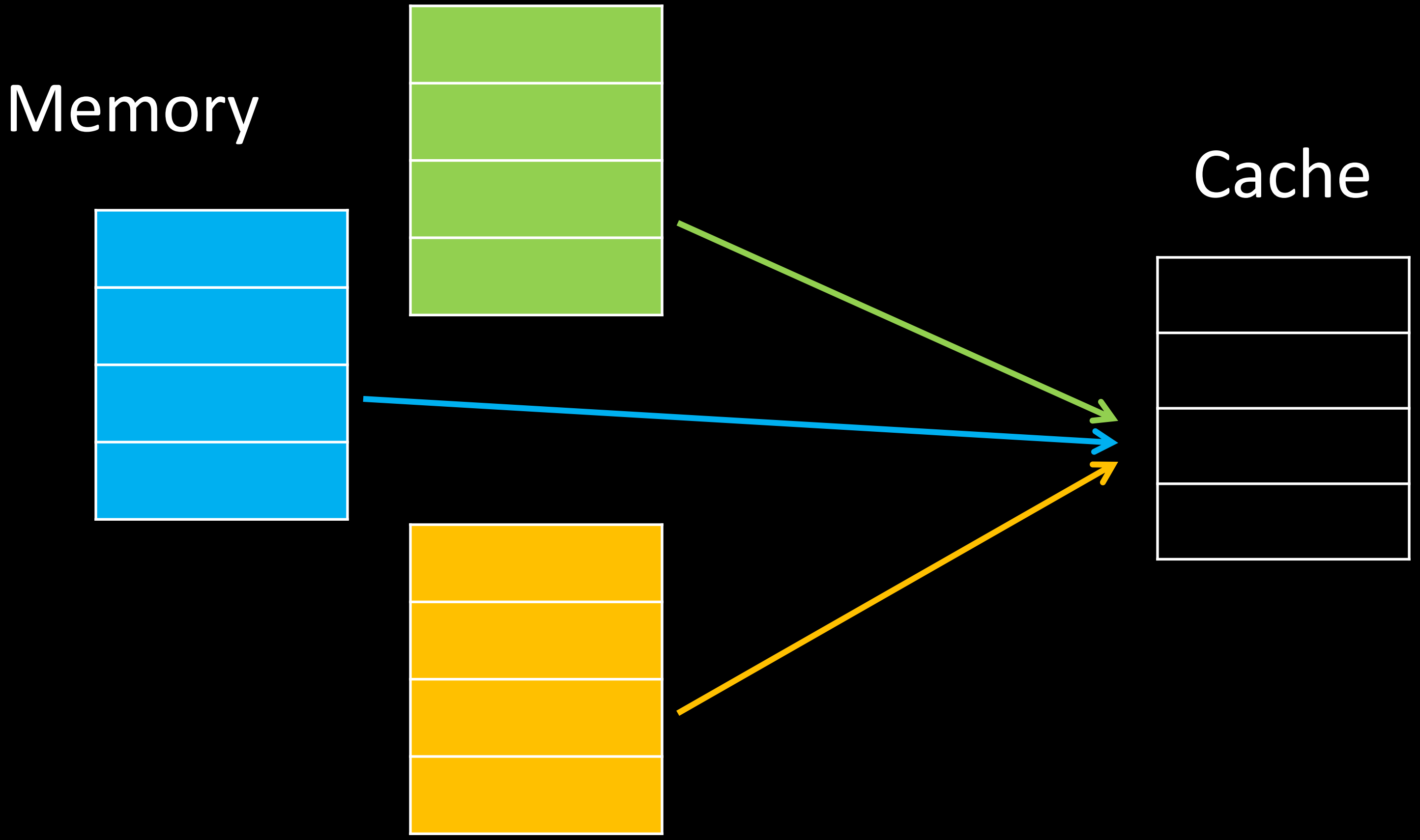

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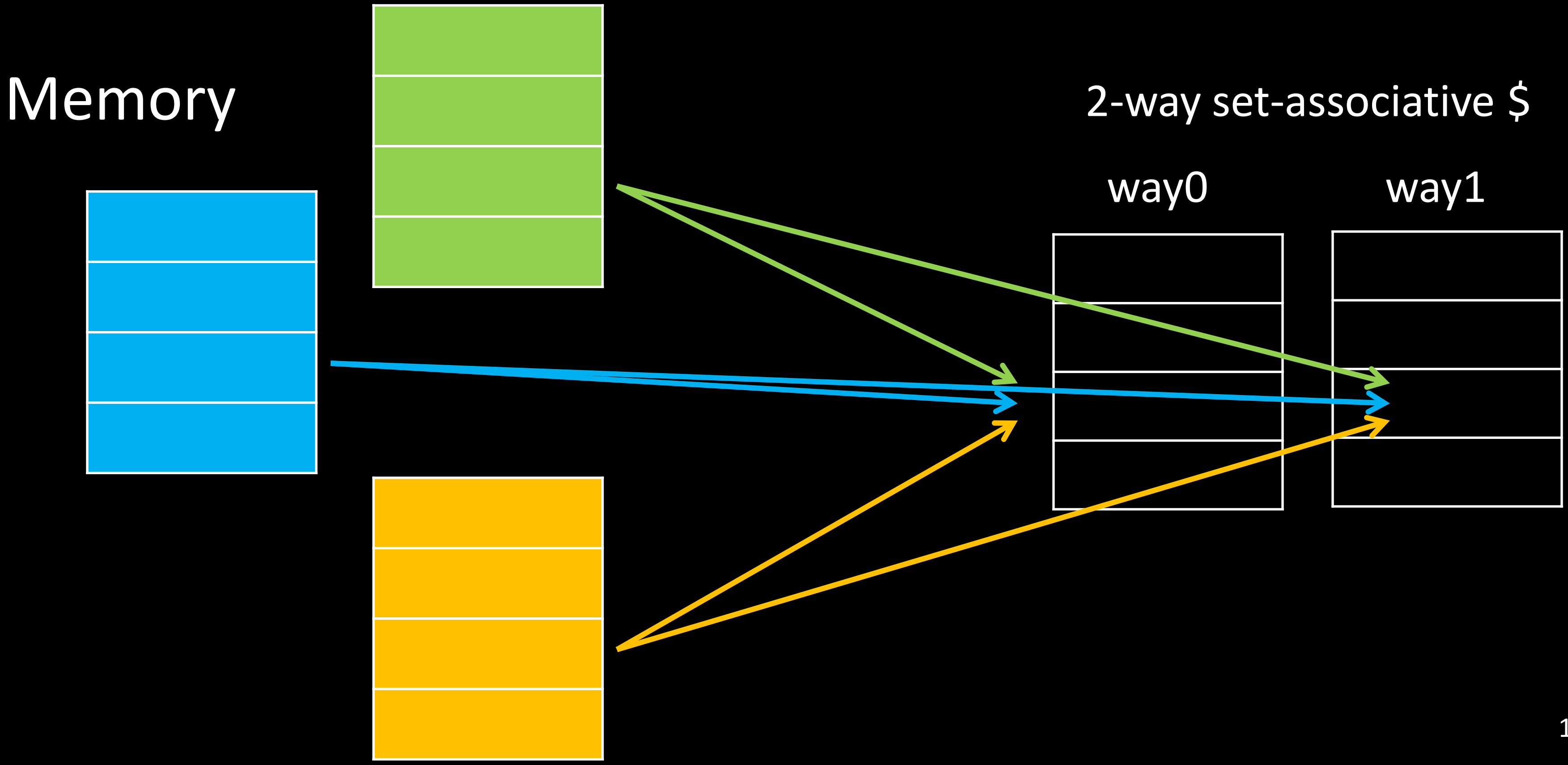
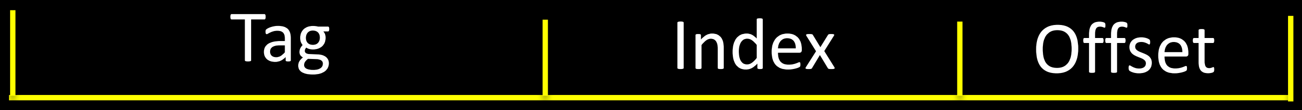


TIO: Mapping the Memory Address

- Lowest bits of address (*Offset*) determine *which byte within a block* it refers to.
- Full address format:



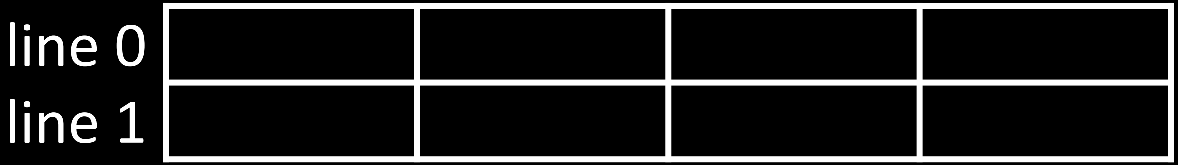
Memory Address

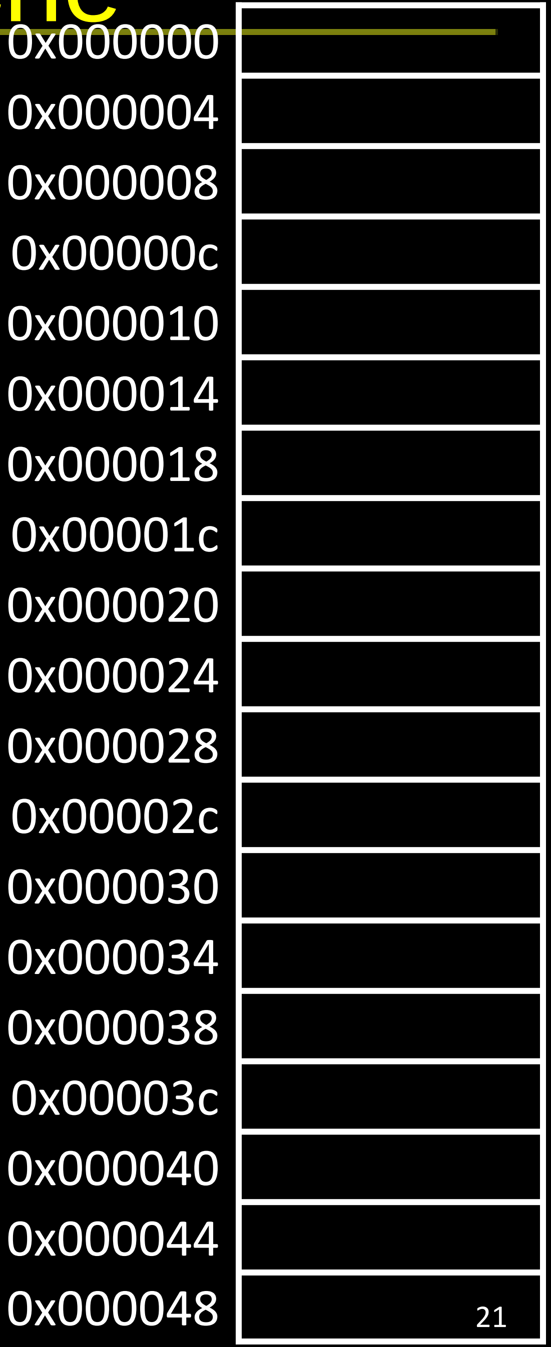
- n-bit Offset means a block is how many bytes?
- n-bit Index means cache has how many blocks?

Direct Mapped Cache

Direct Mapped Cache

- Each block number mapped to a single cache line index
- Simplest hardware





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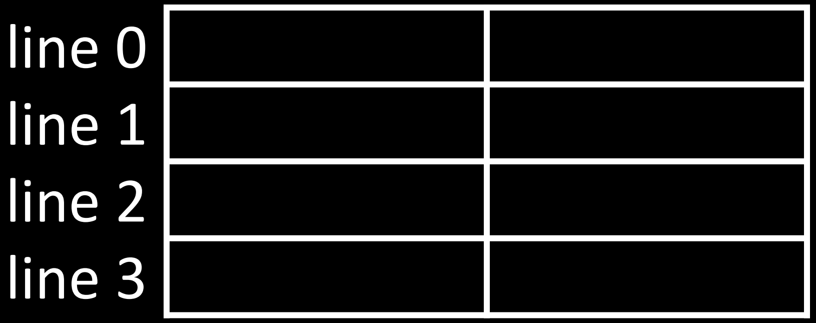
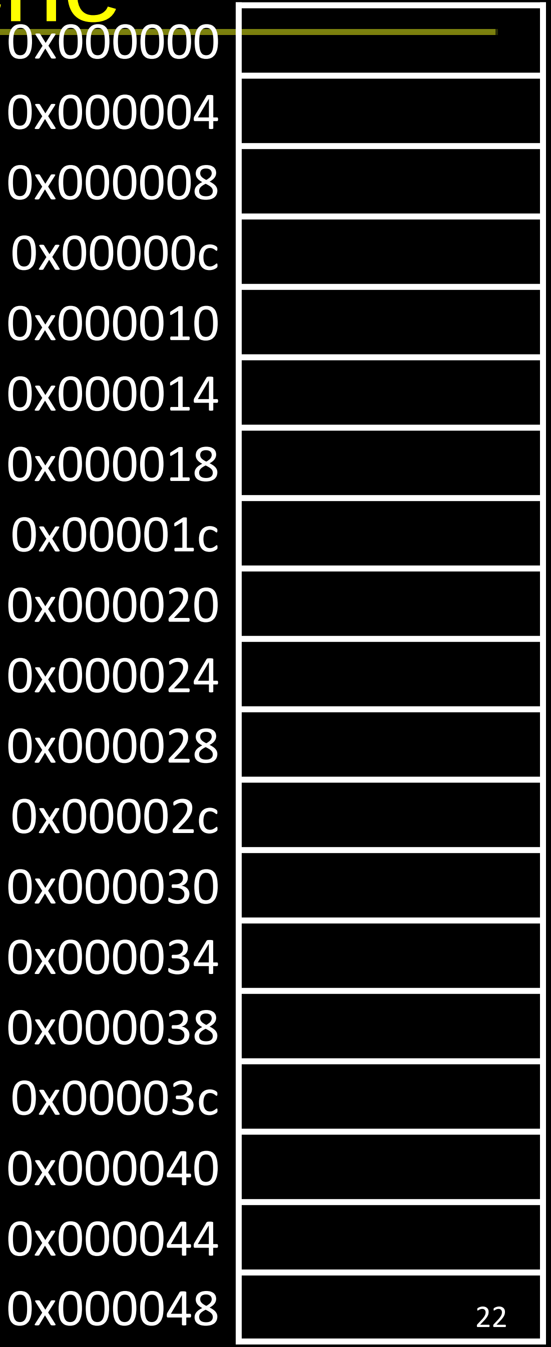




Tags and Offsets

Assume sixteen 64-byte cache lines

0x7FFF3D4D
  = 0111 1111 1111 1111 0011 1101 0100 1101

Need meta-data for each cache line:

- valid bit: is the cache line non-empty?
- tag: which block is stored in this line (if valid)

Q: how to check if X is in the cache?

Q: how to clear a cache line?

A Simple Direct Mapped Cache

Using **byte addresses** in this example! Addr Bus = 5 bits

Processor

lb $1 ← M[1]
lb $2 ← M[13]
lb $3 ← M[0]
lb $3 ← M[6]
lb $2 ← M[5]
lb $2 ← M[6]
lb $2 ← M[10]
lb $2 ← M[12]

$1	
$2	
$3	
$4	

Direct Mapped Cache

A =

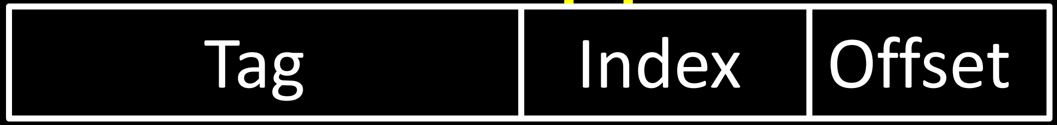
V	tag	data	

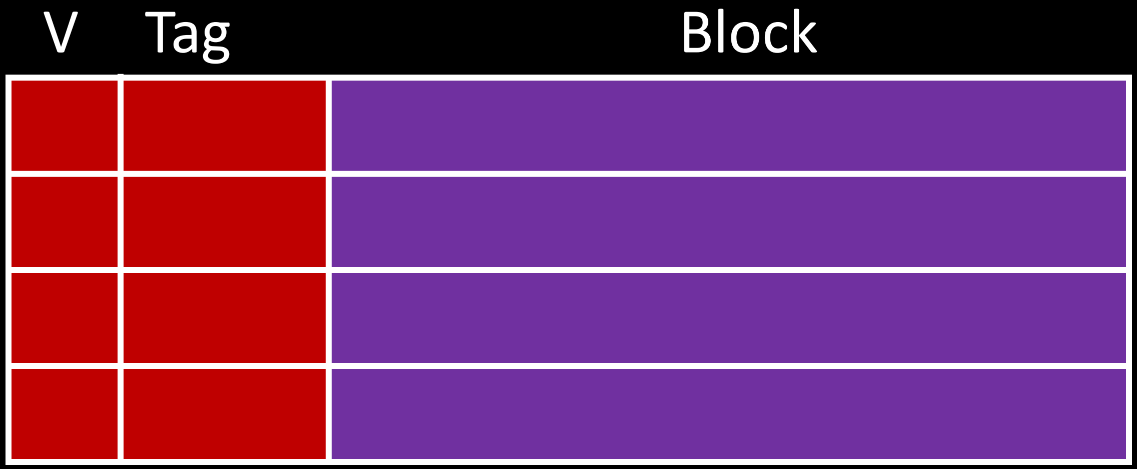
Hits: Misses:

Memory

0	101
1	103
2	107
3	109
4	113
5	127
6	131
7	137
8	139
9	149
10	151
11	157
12	163
13	167
14	173
15	179
16	181

Direct Mapped Cache (Reading)





Direct Mapped Cache Size

Tag	Index	Offset

n bit index, *m* bit offset

Q: How big is cache (data only)?

Q: How much SRAM needed (data + overhead)?

Cache Performance

Cache Performance (very simplified):

- L1 (SRAM): 512 x 64 byte cache lines, direct mapped
  - Data cost: 3 cycle per word access
  - Lookup cost: 2 cycle
- Mem (DRAM): 4GB
  - Data cost: 50 cycle per word, plus 3 cycle per consecutive word

Performance depends on:

- Access time for hit, miss penalty, hit rate

Misses

Cache misses: classification

The line is being referenced for the first time

- Cold (aka Compulsory) Miss

The line was in the cache, but has been evicted

Avoiding Misses

Q: How to avoid…

Cold Misses

- Unavoidable? The data was never in the cache…
- Prefetching!

Other Misses

- Buy more SRAM
- Use a more flexible cache design

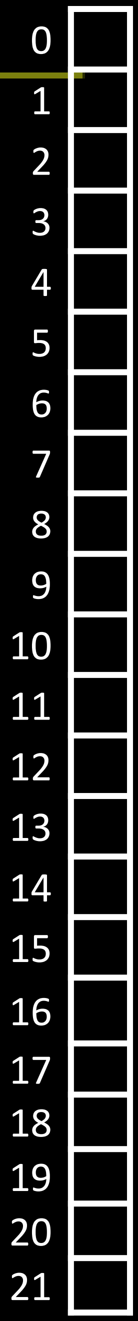
Bigger cache doesn't always help…

Mem access trace: 0, 16, 1, 17, 2, 18, 3, 19, 4, …

Hit rate with four direct-mapped 2-byte cache lines?

With eight 2-byte cache lines?

With four 4-byte cache lines?



Misses

Cache misses: classification

The line is being referenced for the first time

- Cold (aka Compulsory) Miss

The line was in the cache, but has been evicted…

… because some other access with the same index

- Conflict Miss

… because the cache is too small

- i.e. the *working set* of program is larger than the cache
- Capacity Miss

Avoiding Misses

Q: How to avoid…

Cold Misses

- Unavoidable? The data was never in the cache…
- Prefetching!

Capacity Misses

- Buy more SRAM

Conflict Misses

- Use a more flexible cache design

Three common designs

A given data block can be placed…

- … in any cache line → Fully Associative
- … in exactly one cache line → Direct Mapped
- … in a small set of cache lines → Set Associative

A Simple Fully Associative Cache

Using **byte addresses** in this example! Addr Bus = 5 bits

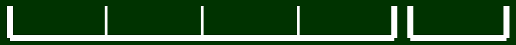
Processor

lb $1 ← M[1]
lb $2 ← M[13]
lb $3 ← M[0]
lb $3 ← M[6]
lb $2 ← M[5]
lb $2 ← M[6]
lb $2 ← M[10]
lb $2 ← M[12]

$1	
$2	
$3	
$4	

Fully Associative Cache

A =



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Hits: Misses:

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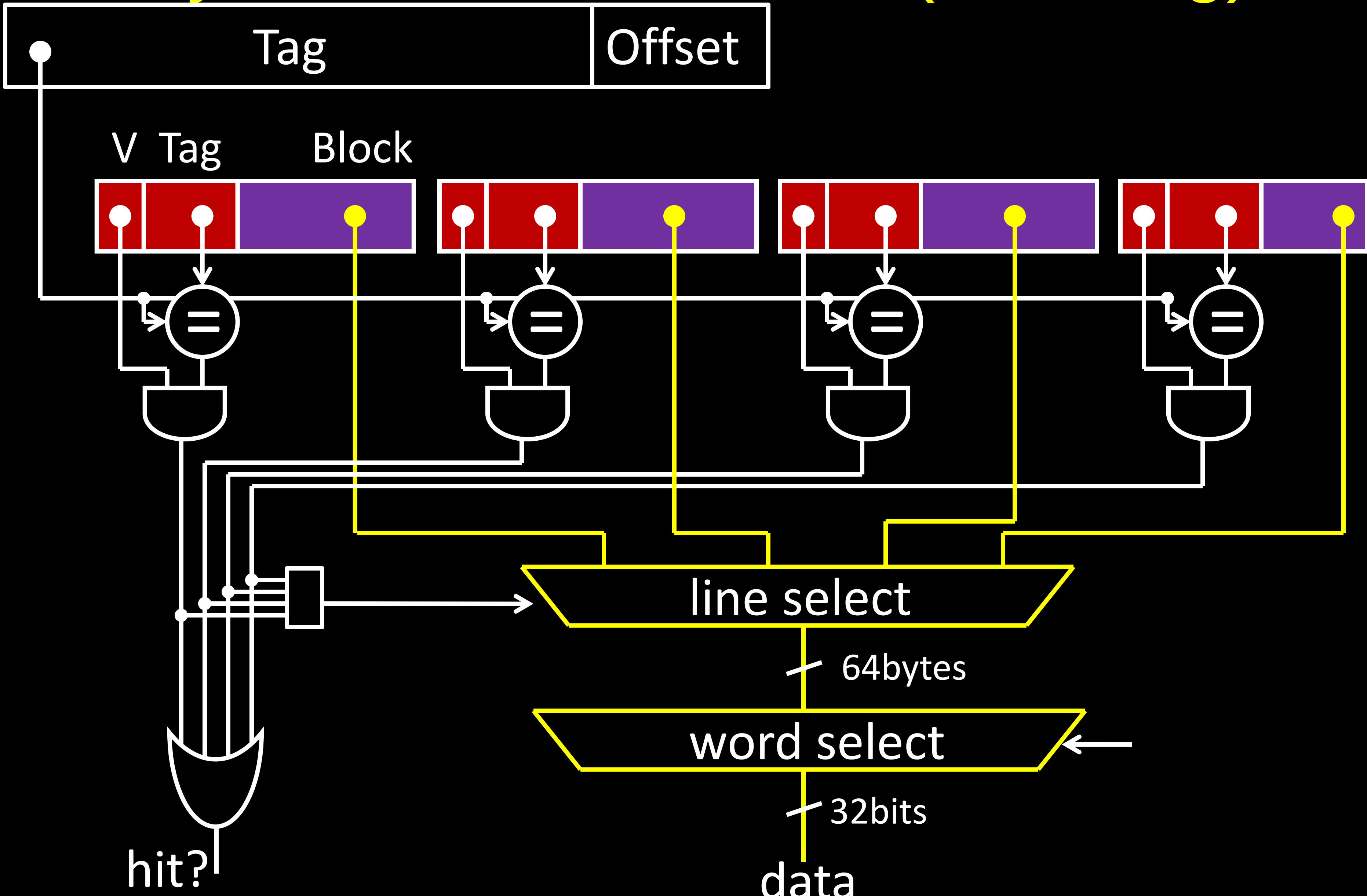
Fully Associative Cache (Reading)



Fully Associative Cache Size

Tag	Offset

m bit offset , 2^n cache lines

Q: How big is cache (data only)?

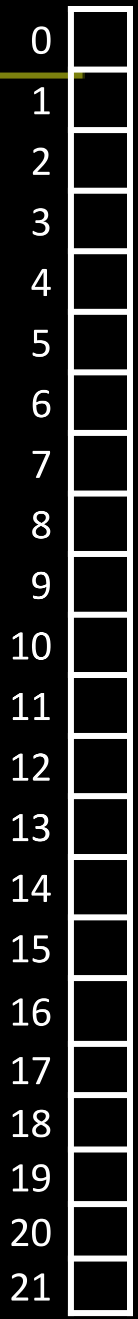
Q: How much SRAM needed (data + overhead)?

Fully-associative reduces conflict misses...

… assuming good eviction strategy

Mem access trace: 0, 16, 1, 17, 2, 18, 3, 19, 4, 20, …

Hit rate with four fully-associative 2-byte cache lines?



… but large block size can still reduce hit rate

vector add trace: 0, 100, 200, 1, 101, 201, 2, 202, …

Hit rate with four fully-associative 2-byte cache lines?

With two fully-associative 4-byte cache lines?

Misses

Cache misses: classification

Cold (aka Compulsory)

- The line is being referenced for the first time

Capacity

- The line was evicted because the cache was too small
- i.e. the *working set* of program is larger than the cache

Conflict

- The line was evicted because of another access whose index conflicted

Summary

Caching assumptions

- small working set: 90/10 rule
- can predict future: spatial & temporal locality

Benefits

- big & fast memory built from (big & slow) + (small & fast)

Tradeoffs:

associativity, line size, hit cost, miss penalty, hit rate

- Fully Associative → higher hit cost, higher hit rate
- Larger block size → lower hit cost, higher miss penalty

Next up: other designs; writing to caches