CSE 351

Caches

Agenda

- Upcoming Deadlines
  - Lab 3 due Friday 11/13 at 5:00pm
  - HW 3 will be released Friday, due Friday 11/20
- Section Survey
- Introduction to Caches
- Midterm and Lab 3 Questions?

Feedback for your TA

- In general, pace of this section is:
  1. too **fast**
  2. kind of fast
  3. just right
  4. kind of slow
  5. too **slow**
- Please **Keep** doing this:
- Please **Stop** doing this:
- Please **Start** doing this:

Performance Bottlenecks

- How do we define "computer performance"
  - Instruction throughput, i.e. how many instructions can we execute per second?
- What factors affect this?
  - CPU architecture gives an estimate for maximum instructions per second (IPS)
  - However, the CPU can only process data at the rate it receives the data
  - Reading from memory has become increasingly slow relative to the rate at which modern processors can execute instructions
  - Memory is a bottleneck!

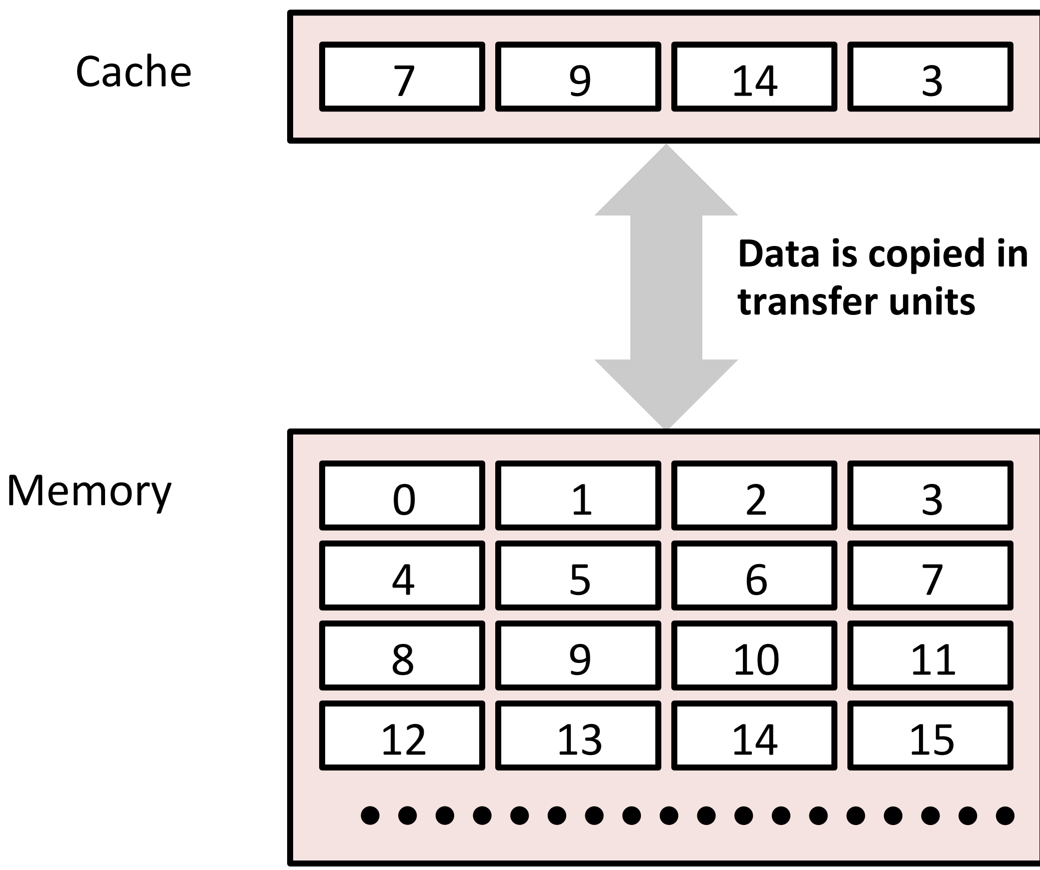
What is a Cache?

- A CPU cache is a small, fast region of memory that is actually on the same piece of silicon as the processor
  - Modern processors have as many as 4 caches, each progressively larger and slower
  - They form a cache hierarchy
- Caches are orders of magnitude faster than the DRAM used for main memory
- However, they fill up quickly, so the CPU needs to be smart about how it uses caches

Caches Improve Performance

- Data caching is a common optimization in many systems
- Example: Web Browsers
  - Network latency is a bottleneck
  - Web browsers can't display pages until they have received the data
  - Your web browser caches static files (images, .html, .css, .js, etc) that you have recently downloaded onto your hard drive
  - Relative to the network, your hard drive is speedy
- Processors use the same concept to improve performance, by caching data as well as instructions

General Cache Mechanics

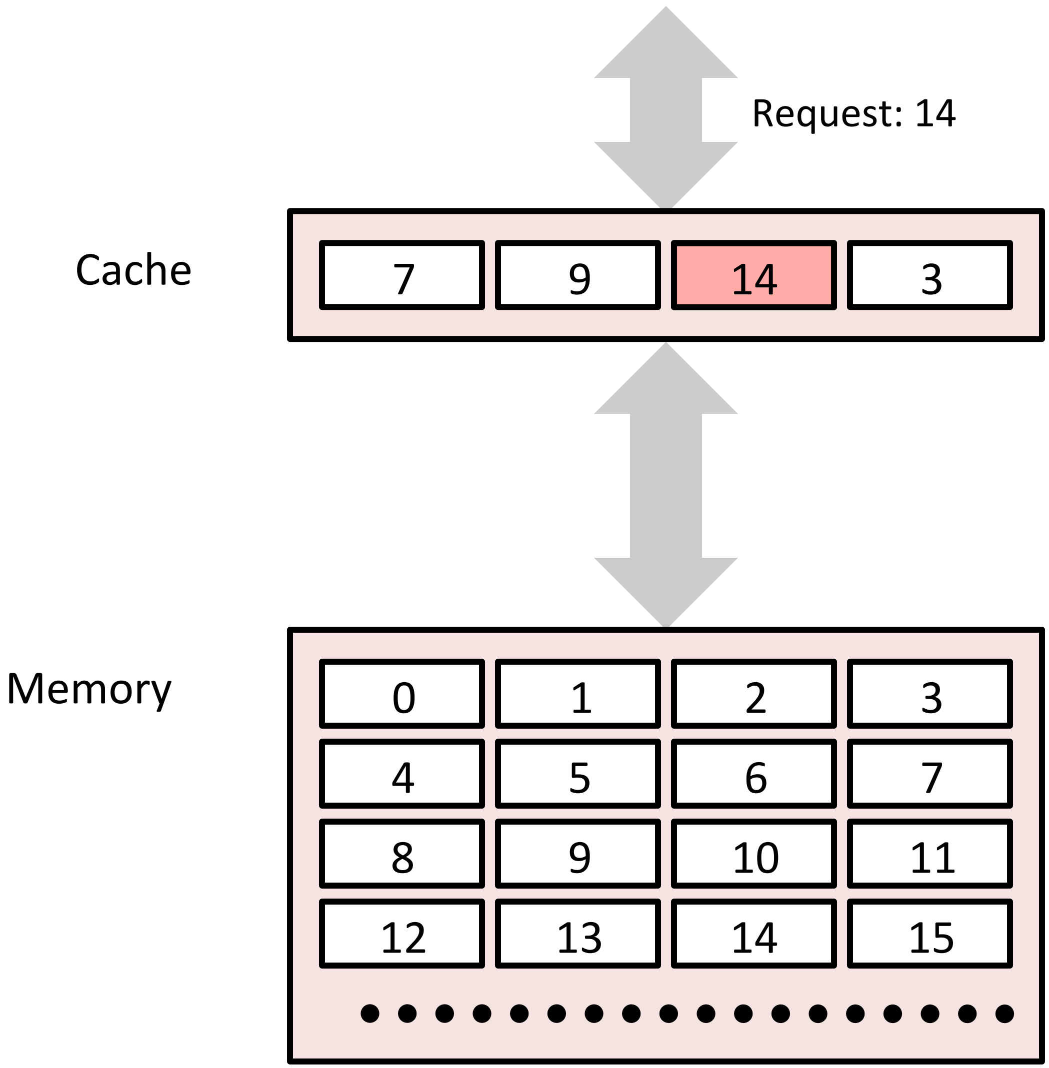


- **Smaller, faster, more expensive memory.**
- **Caches a subset of the blocks (a.k.a. lines)**

Data is copied in block-sized transfer units

- **Larger, slower, cheaper memory.**
- **Viewed as partitioned into "blocks" or "lines"**

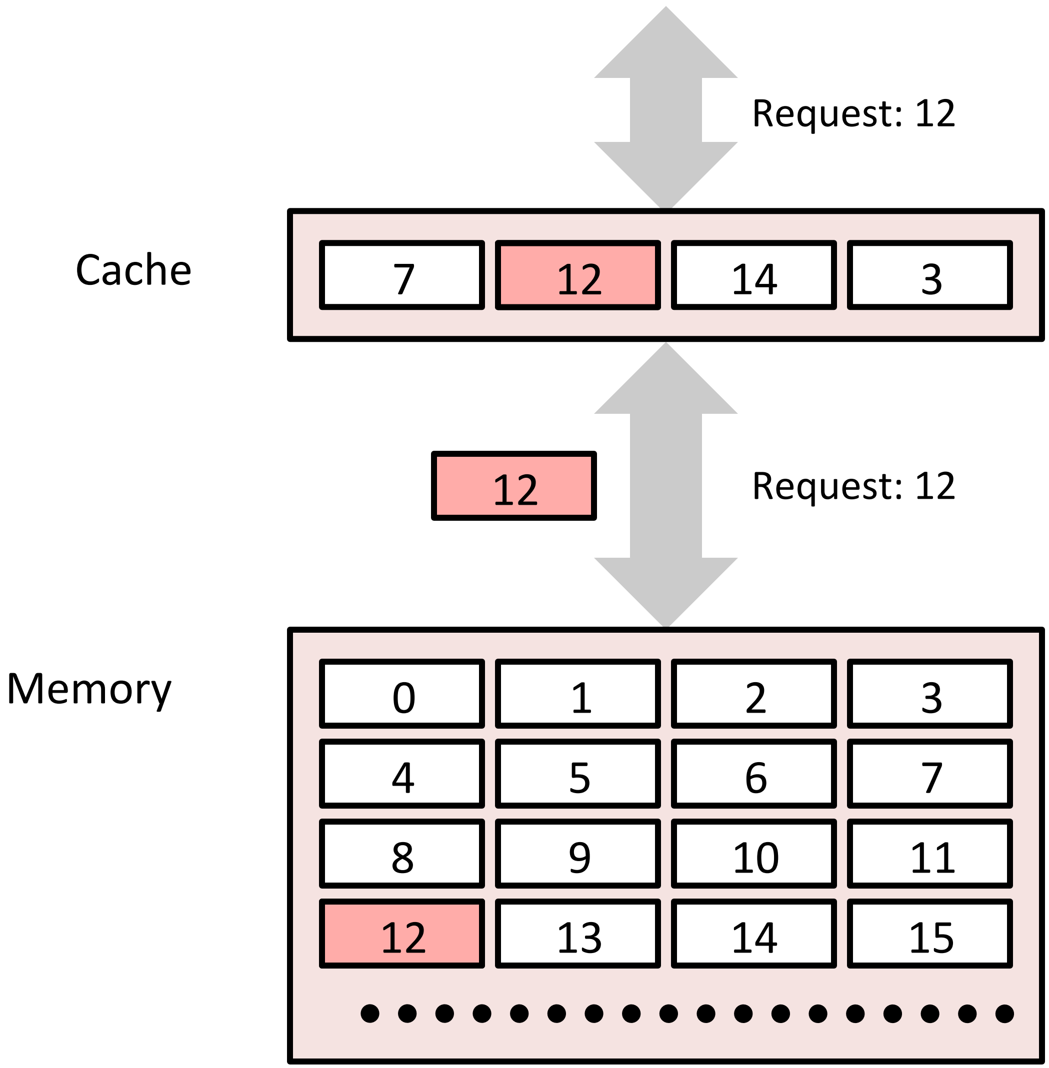
General Cache Concepts: Hit



Data in block b is needed

Block b is in cache:
Hit!

General Cache Concepts: Miss



Data in block b is needed

Block b is not in cache: Miss!

***Block b is fetched from** memory*

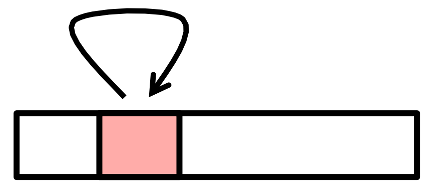
Block b is stored in cache

- Placement policy: determines where b goes
- Replacement policy: determines which block gets evicted (victim)

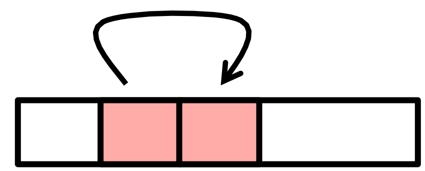
Why Caches Work

Locality: Programs tend to use data and instructions with addresses near or equal to those they have used recently

- Temporal locality:
  - Recently referenced items are *likely* to be referenced again in the near future



- Spatial locality:
  - Items with nearby addresses *tend* to be referenced close together in time

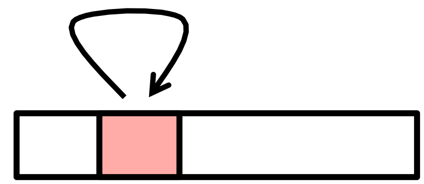


  - How do caches take advantage of these access patterns?

Why Caches Work

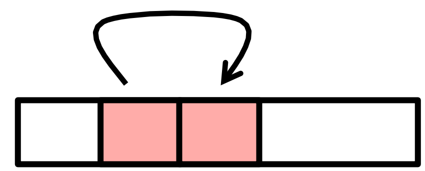
Locality: Programs tend to use data and instructions with addresses near or equal to those they have used recently

- Temporal locality:
  - Recently referenced items are *likely* to be referenced again in the near future
  - Recently referenced memory locations are stored in the cache



block

- Spatial locality:
  - Items with nearby addresses *tend* to be referenced close together in time
  - Nearby addresses are moved to the cache when one is needed



block

Locality Examples

```
x = a + 6;
y = a + 5;
z = 8 * a;
```

Temporal: `a` is accessed multiple times

```
x = b[0] + 6;
y = b[1] + 5;
z = 8 * b[2];
```

Spatial: increasing indices of `b` are accessed in sequence

Example: Any Locality?

```
sum = 0;
for (i = 0; i < n; i++)
        sum += a[i];
return sum;
```

- Data:
  - **Temporal**: **`sum`** referenced in each iteration
  - **Spatial**: array **`a[]`** accessed in stride-1 pattern
- Instructions:
  - **Temporal**: cycle through loop repeatedly
  - **Spatial**: reference instructions in sequence

- Being able to assess the locality of code is a crucial skill for a programmer

Where is the Locality?

```
for (i = 1; i < 100; i++) {
        a = a * 7;
        b = b + x[i];
        c = y[5] + d;
}
```

- Remember: accessing arrays doesn’t automatically mean spatial or any locality since you could access the indices in random order

Locality Example #1

```
int sum_array_rows(int a[M][N])
{
    int i, j, sum = 0;

    for (i = 0; i < M; i++)
        for (j = 0; j < N; j++)
            sum += a[i][j];
    return sum;
}
```

M = 3, N=4

a[0][0]	a[0][1]	a[0][2]	a[0][3]
a[1][0]	a[1][1]	a[1][2]	a[1][3]
a[2][0]	a[2][1]	a[2][2]	a[2][3]

Layout in Memory

a [0] [0]	a [0] [1]	a [0] [2]	a [0] [3]	a [1] [0]	a [1] [1]	a [1] [2]	a [1] [3]	a [2] [0]	a [2] [1]	a [2] [2]	a [2] [3]
76				92				108			

Order Accessed

1: a[0][0]
2: a[0][1]
3: a[0][2]
4: a[0][3]
5: a[1][0]
6: a[1][1]
7: a[1][2]
8: a[1][3]
9: a[2][0]
10: a[2][1]
11: a[2][2]
12: a[2][3]

stride-1

Locality Example #2

```
int sum_array_cols(int a[M][N])
{
    int i, j, sum = 0;

    for (j = 0; j < N; j++)
        for (i = 0; i < M; i++)
            sum += a[i][j];
    return sum;
}
```

M = 3, N=4

a[0][0]	a[0][1]	a[0][2]	a[0][3]
a[1][0]	a[1][1]	a[1][2]	a[1][3]
a[2][0]	a[2][1]	a[2][2]	a[2][3]

Layout in Memory

a [0] [0]	a [0] [1]	a [0] [2]	a [0] [3]	a [1] [0]	a [1] [1]	a [1] [2]	a [1] [3]	a [2] [0]	a [2] [1]	a [2] [2]	a [2] [3]

76 92 108

Order Accessed

1: a[0][0]
2: a[1][0]
3: a[2][0]
4: a[0][1]
5: a[1][1]
6: a[2][1]
7: a[0][2]
8: a[1][2]
9: a[2][2]
10: a[0][3]
11: a[1][3]
12: a[2][3]

stride-N

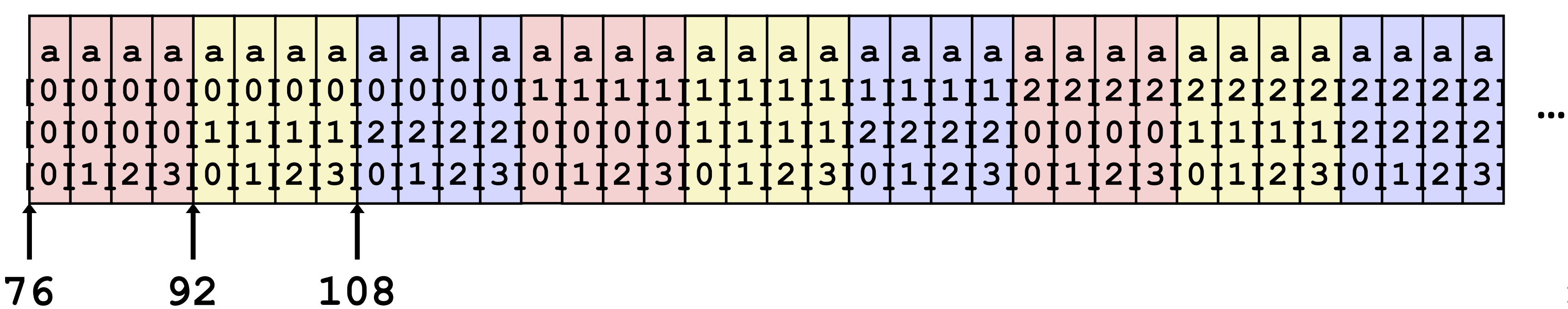
Locality Example #3

```
int sum_array_3d(int a[M][N][L])
{
    int i, j, k, sum = 0;

    for (i = 0; i < N; i++)
        for (j = 0; j < L; j++)
            for (k = 0; k < M; k++)
                sum += a[k][i][j];
    return sum;
}
```

- What is wrong with this code?
- How can it be fixed?

Layout in Memory (for M = ?, N = 3, L=4)



Locality and Data Structures

- Which has (at least the potential for) better spatial locality, arrays or linked lists?

Locality and Data Structures

- Which has (at least the potential for) better spatial locality, arrays or linked lists?
- Nodes in a linked list are not allocated contiguously
- On the other hand, array elements are allocated contiguously
- What about node fields? Data, next, and other fields could be allocated contiguously