CSE373: Data Structures & Algorithms
Lecture 26: Memory Hierarchy and Locality

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Why do we need to know about the memory Hierarchy?

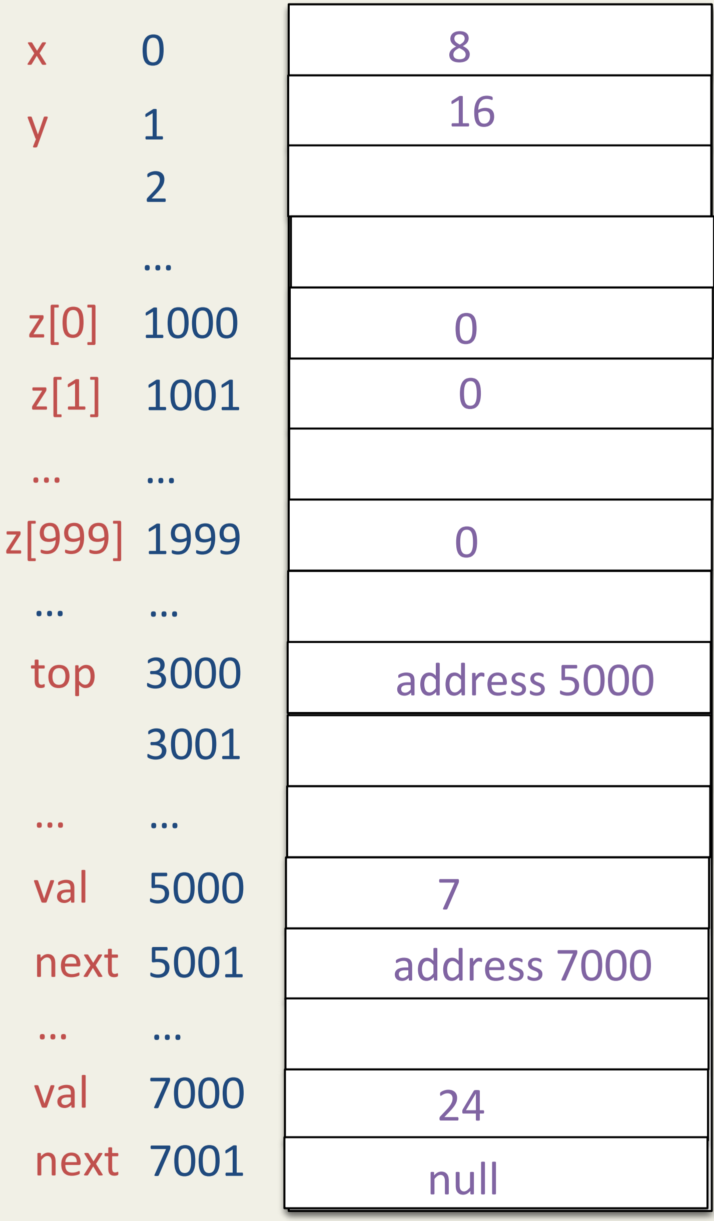
- One of the assumptions that Big-Oh makes is that all operations take the same amount of time
  - This is not quite correct.

Example

```
int x = 8;
int y = 2 * x;

int[] z = new int[1000]
int val = a[0] + a[1] + a[999];

ListNode top = new ListNode(7);
top.next = new ListNode(24);
ListNode temp = top.next;
```



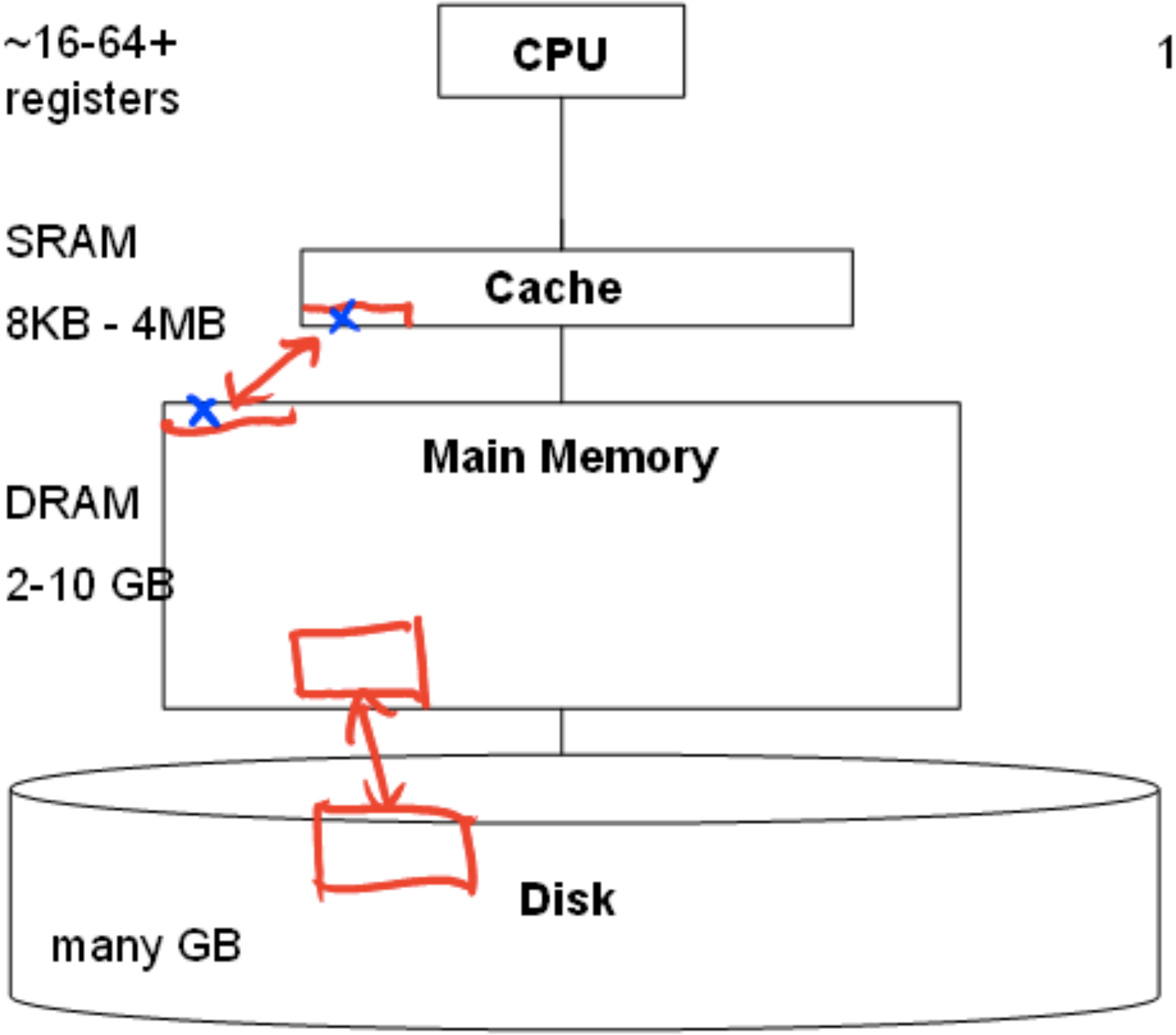
x	0	8
y	1	16
	2	
	…	
z[0]	1000	0
z[1]	1001	0
…	…	
z[999]	1999	0
…	…	
top	3000	address 5000
	3001	
…	…	
val	5000	7
next	5001	address 7000
…	…	
val	7000	24
next	7001	null

Definitions

- **Cycle** (for our purposes): the time is takes to execute a single simple instruction (for example, add 2 registers together)

- **Memory Latency**: The time it takes to access memory

TIme to access:



CPU

~16-64+ registers

1 ns per instruction

Cache

SRAM

8KB - 4MB

Cache

2-10 ns

Main Memory

DRAM

2-10 GB

Main Memory

40-100 ns

Disk

many GB

Disk a few *milli*seconds

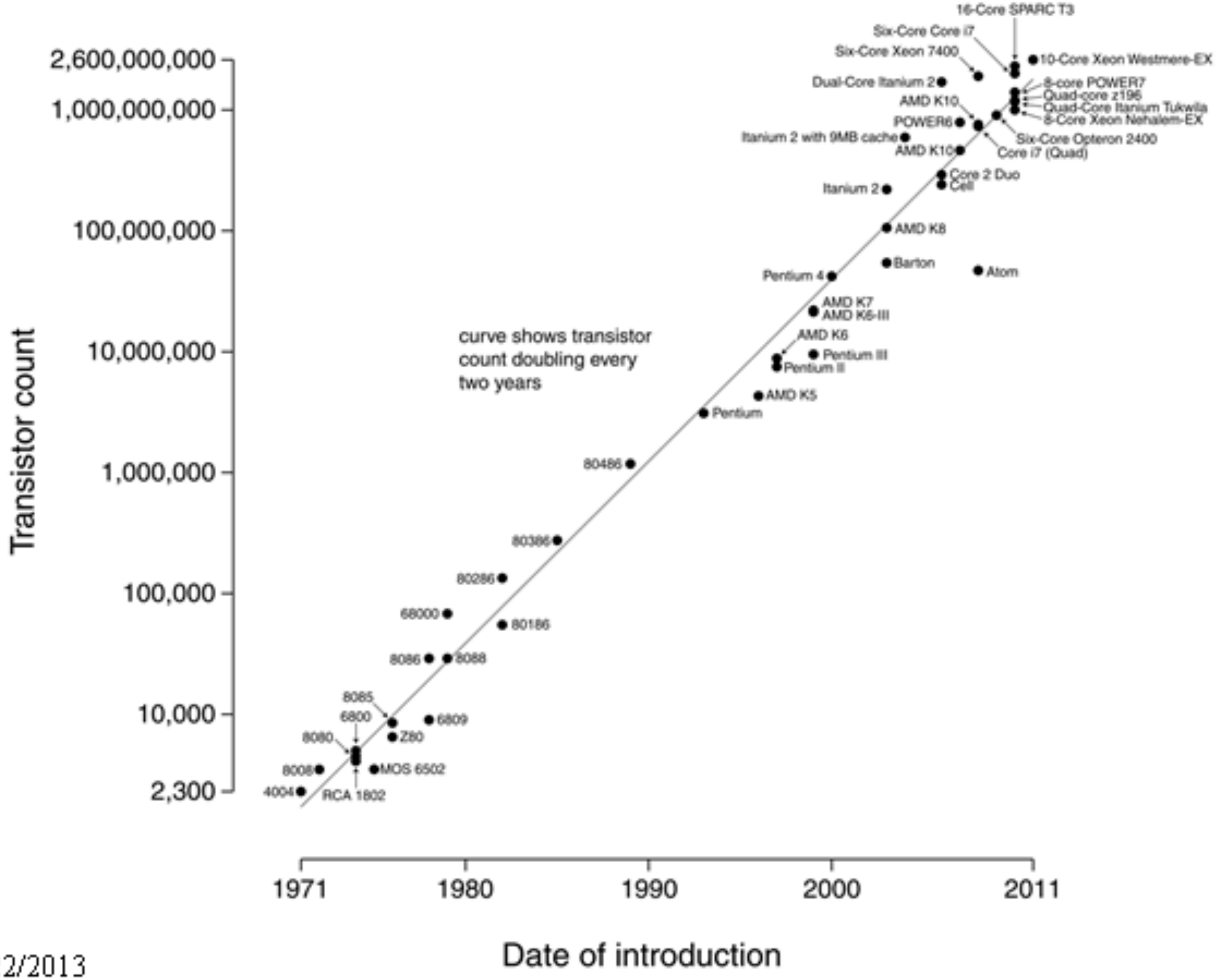
(5-10 *Million* ns)

Moral of the story

- It is much faster to do:
  - 5 million arithmetic ops than 1 disk access
  - 25000 L2 cache accesses than 1 disk access
  - 400 main memory accesses then 1 disk access

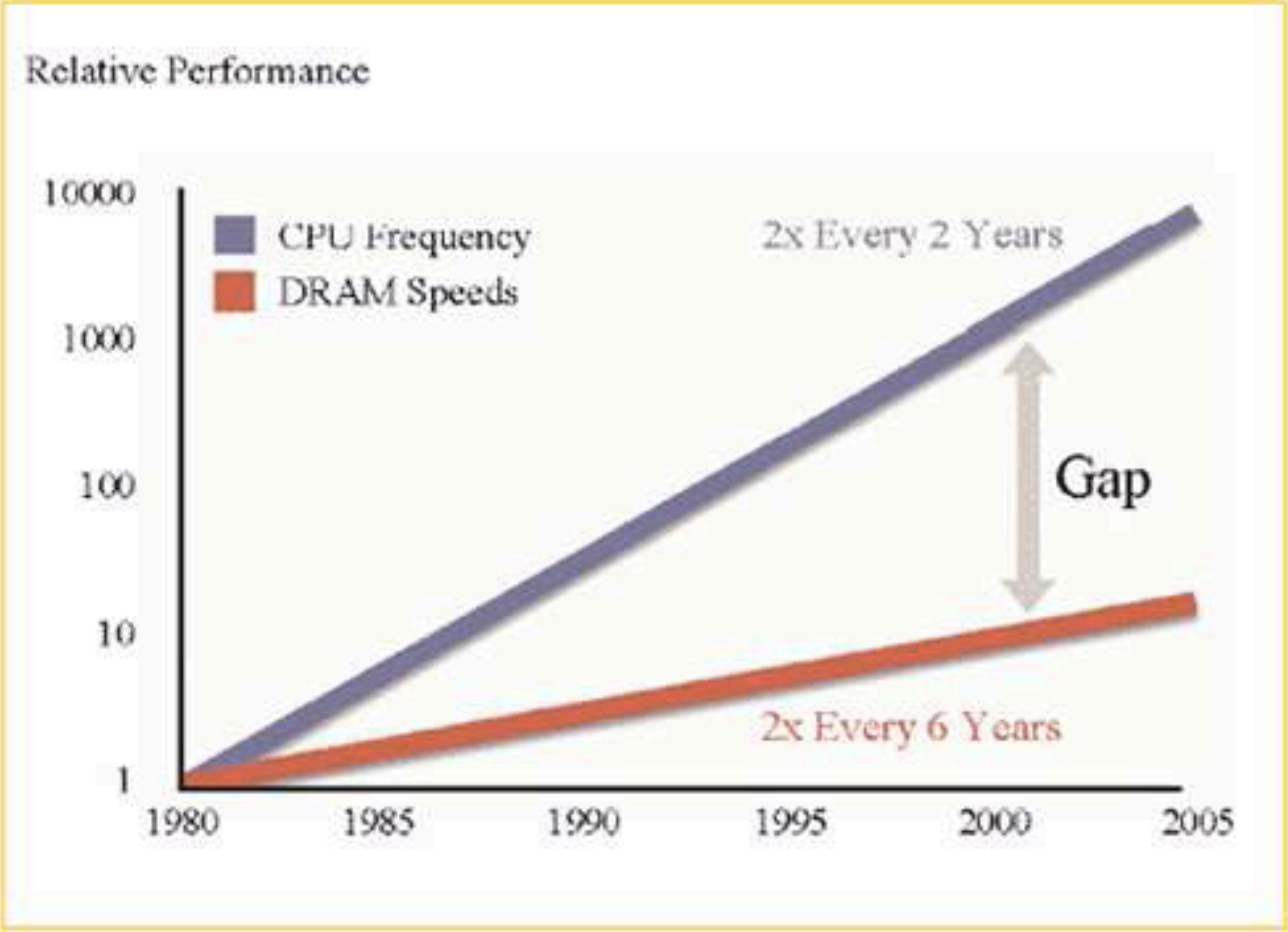
- **Why though?**
  - Physical realities (speed of light, closeness to CPU)
  - Cost (price per byte of different technologies)
  - Disks get much **bigger** but not much **faster**
    - Spinning at 7200 RPM account for much of the slowness, spinning hard disks are unlikely to get much faster.
    - What about SSDs?
  - Speedup at higher levels (i.e. a faster processor) makes lower level accesses relatively slower. Yikes.

Microprocessor Transistor Counts 1971-2011 & Moore's Law



From Wikipedia

Processor-Memory Performance Gap



http://www.mentor.com

What can we do to optimize?

- Hardware automatically moves data into caches from main memory
  - Replacing items already there
  - Algorithms are much faster if data fits in the cache

- Disk accesses are abstracted away by the operating system

- Code “just runs” but sometimes it’s worth designed algorithms/data structures with knowledge of the memory hierachy

Locality

- **Temporal Locality** (locality in time)
  - If an item (a location in memory) is referenced, *that same location* will tend to be referenced again soon

- **Spatial Locality** (locality in space)
  - If an item is referenced, items *whose addresses are close by* will tend to be referenced soon as well

How does data move up the hierarchy?

- Moving data up the hierarchy is slow because of latency (distance to travel)
  - Since we are making a trip anyway, might as well carpool!
    - Get a block of data in the same time it takes to get a byte
  - Send nearby memory
    - Because its cheap and easy
    - And spatial locality says it will be asked for soon!

- Once we move something to the cache, keep it around for a while, no rush to get rid of it! (Temporal Locality)

Cache Facts

- Each level is a sub-set of the level below

- Definitions
  - **Cache hit:** address requested already in the cache
  - **Cache miss:** address request NOT in the cache
  - **Block of page size:** the number of contiguous bytes moved from disk to memory
  - **Cache line size**: the number of contiguous bytes moved from memory to the cache

Examples

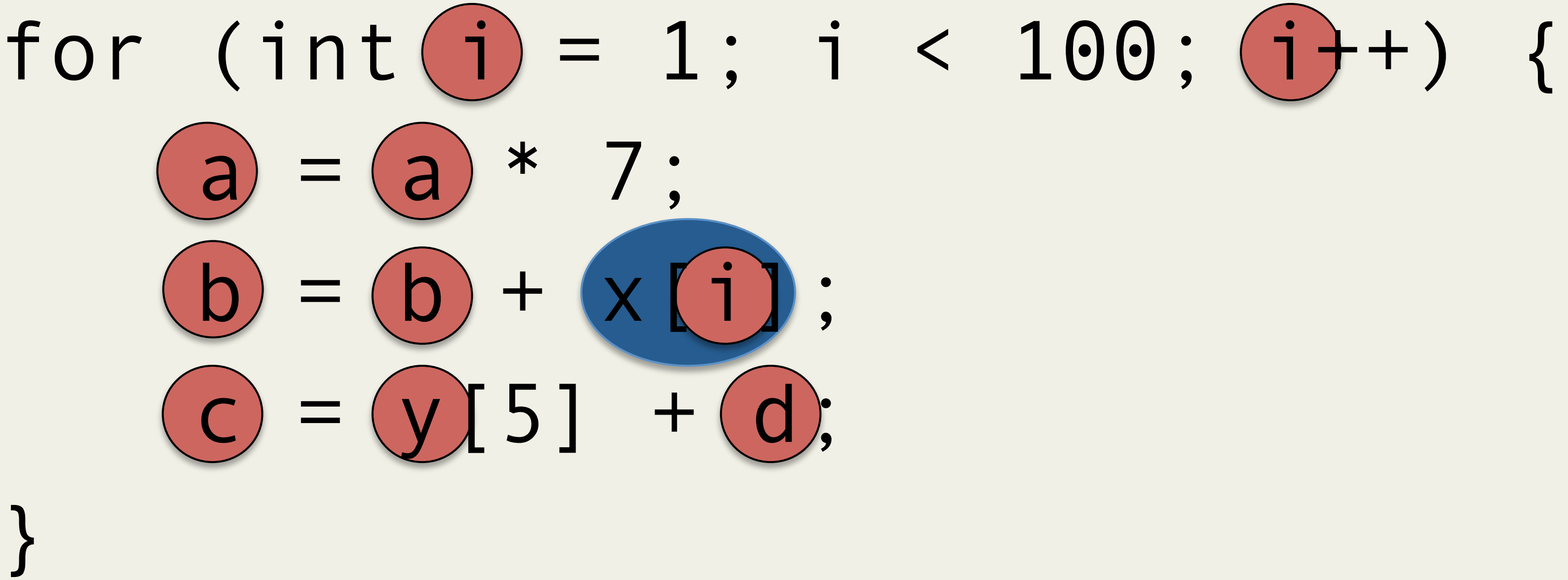
```
x = a + 6;        miss
y = a + 5;        hit        Temporal
z = 8 * a;        hit        Locality

x = a[0];         miss
y = a[1] + 5;     hit        Spatial
z = 8 * a[2];     hit        Locality
```

Locality in Data Structure

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

Where is the locality?



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

🔵 = Spatial Locality on locations in array x

🔴 = Temporal Locality