Why do we need to know about the memory hierarchy/locality?

- One of the assumptions that Big-Oh makes is that *all operations take the same amount of time*.
- Is that really true?

Where are these values in memory?

```
x = y + z;
i++;
z = a[0] + a[1];
y = a[2] + a[5000];
```

```java
ListNode top = new ListNode(7);
top.next = new ListNode(26);
ListNode temp = top.next;
```
Morals

It is much faster to do: Than:
5 million arithmetic ops 1 disk access
2500 L2 cache accesses 1 disk access
400 main memory accesses 1 disk access

Why are computers built this way?
- Physical realities (speed of light, closeness to CPU)
- Cost (price per byte of different technologies)
- Disks get much bigger not much faster
  - Spinning at 7200 RPM accounts for much of the slowness and unlikely to spin faster in the future
- Speedup at higher levels (e.g., a faster processor) makes lower levels relatively slower. Agh!

Moore’s Law

Processor-Memory Performance Gap

- x86 CPU speed (100x over 10 years)

What can be done?
- **Goal**: Attempt to reduce the number of accesses to the slower levels.
- **How**?

So, what can we do?

The hardware automatically moves data into the caches from main memory for you
- Replacing items already there
- Algorithms are much faster if “data fits in cache” (often does)

Disk accesses are done by software (e.g., ask operating system to open a file or database to access some data)

So most code “just runs” but sometimes it’s worth designing algorithms / data structures with knowledge of memory hierarchy
- And when you do, you often need to know one more thing…

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.
How does data move up the hierarchy?

- Moving data up the memory hierarchy is slow because of latency (think distance-to-travel)
  - Since we’re making the trip anyway, may as well carpool
    - Get a block of data in the same time it would take to get a byte
  - Sends nearby memory because:
    - It’s easy
    - Nearby memory is likely to be asked for soon (think fields/arrays)
- Side note: Once a value is in cache, may as well keep it around for awhile; accessed once, a value is more likely to be accessed again in the near future (more likely than some random other value)

Temporal locality

Spatial Locality

Cache Facts

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

Definitions:
- Cache Hit – address requested is in cache
- Cache Miss – address requested is NOT in cache
- Block or Page size - the number of contiguous bytes moved from disk into memory
- Cache line size - the number of contiguous bytes moved from memory into cache

Examples

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

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

Locality and Data Structures

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

Where is the Locality?

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