Memory Heirarchies

- One of the great triumphs of computer design
- Effect is a large, fast memory
- Reality is a series of progressively larger, slower, cheaper stores, with frequently accessed data automatically staged to faster storage (cache, main storage, disk)
- Programmer/compiler typically treats it as one large store. Bug or feature?

Memory Issues (review)

- Byte load/store is often slower than whole (physical) word load/store
  - Unaligned access is often extremely slow
- Temporal locality: accesses to recently accessed data will usually find it in the (fast) cache
- Spatial locality: accesses to data near recently used data will usually be fast
  - "near" = in the same cache block
- But – alternating accesses to blocks that map to the same cache block will cause thrashing

Data Alignment

- Data objects (structs) often are similar in size to a cache block (≈ 8 words)
  - ∴ Better if objects don't span blocks
- Some strategies
  - Allocate objects sequentially; bump to next block boundary if useful
  - Allocate objects of same common size in separate pools (all size-2, size-4, etc.)
- Tradeoff: speed for some wasted space

Instruction Alignment

- Align frequently executed basic blocks on cache boundaries (or avoid spanning cache blocks)

- Branch targets (particularly loops) may be faster if they start on a cache line boundary
- Try to move infrequent code (startup, exceptions) away from hot code
- Optimizing compiler should have a basic-block ordering phase (& maybe even loader)

Loop Interchange

- Watch for bad cache patterns in inner loops; rearrange if possible
- Example

```
for (i = 0; i < m; i++)
  for (j = 0; j < n; j++)
    for (k = 0; k < p; k++)
      a[i,k,j] = b[i,j-1,k] + b[i,j,k] + b[i,j+1,k]
```

  - b[i,j+1,k] is reused in the next two iterations, but will have been flushed from the cache by the k loop

Loop Interchange

- Solution for this example: interchange j and k loops

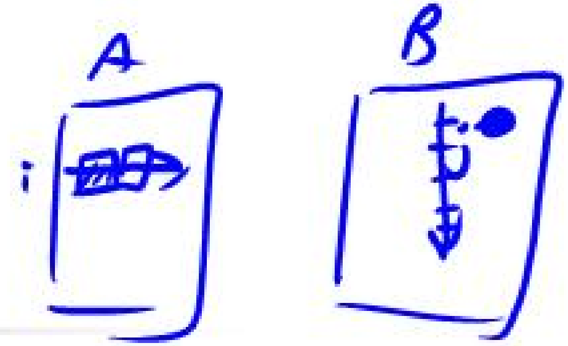
```
for (i = 0; i < m; i++)
  for (k = 0; k < p; k++)
    for (j = 0; j < n; j++)
      a[i,k,j] = b[i,j-1,k] + b[i,j,k] + b[i,j+1,k]
```

  - Now b[i,j+1,k] will be used three times on each cache load
  - Safe here because loop iterations are independent

Loop Interchange

- Need to construct a data-dependency graph showing information flow between loop iterations
- For example, iteration (j,k) depends on iteration (j',k') if (j',k') computes values used in (j,k) or stores values overwritten by (j,k)
  - If there is a dependency and loops are interchanged, we could get different results – so can't do it

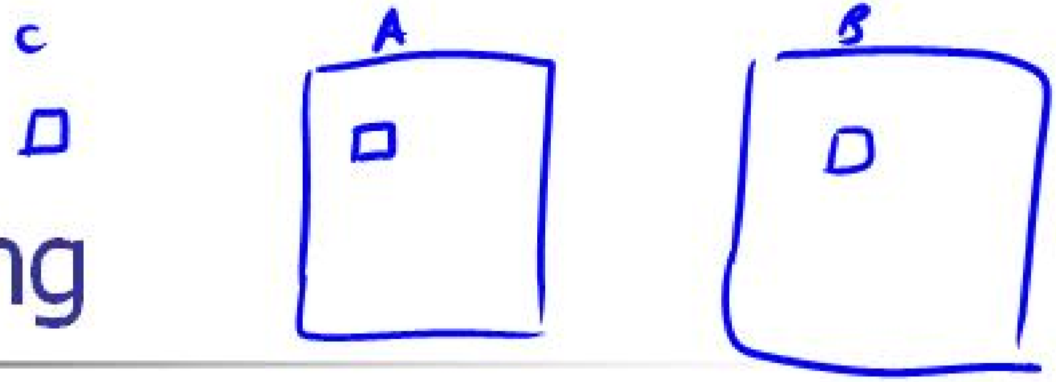
Blocking



- Consider matrix multiply

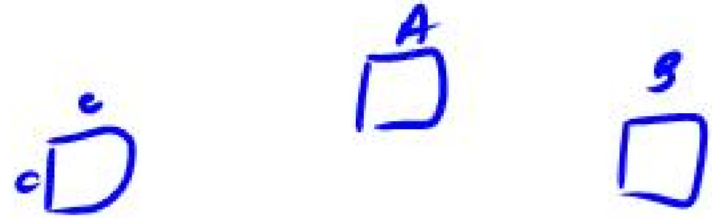
```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++) {
    c[i,j] = 0.0;
    for (k = 0; k < n; k++)
      c[i,j] = c[i,j] + a[i,k]*b[k,j]
  }
```

- If a, b fit in the cache together, great!
- If they don't, then every b[k,j] reference will be a cache miss
- Loop interchange (i<->j) won't help; then every a[i,k] reference would be a miss



Blocking

- Solution: reuse rows of A and columns of B while they are still in the cache
- Assume the cache can hold 2*c*n matrix elements ($1 < c < n$)
- Calculate $c \times c$ blocks of C using c rows of A and c columns of B



Blocking

- Calculating c × c blocks of C

```
for (i = i0; i < i0+c; i++)
  for (j = j0; j < j0+c; j++) {
    c[i,j] = 0.0;
    for (k = 0; k < n; k++)
      c[i,j] = c[i,j] + a[i,k]*b[k,j]
  }
```

Blocking

- Then nest this inside loops that calculate successive c × c blocks

```
for (i0 = 0; i0 < n; i0+=c)
  for (j0 = 0; j0 < n; j0+=c)
    for (i = i0; i < i0+c; i++)
      for (j = j0; j < j0+c; j++) {
        c[i,j] = 0.0;
        for (k = 0; k < n; k++)
          c[i,j] = c[i,j] + a[i,k]*b[k,j]
      }
```

Parallelizing Code

- There is a long literature about how to rearrange loops for better locality and to detect parallelism
- Some starting points
  - Latest edition of *Dragon book*, ch. 11
  - Allen & Kennedy *Optimizing Compilers for Modern Architectures*
  - Wolfe, *High-Performance Compilers for Parallel Computing*