CS 33: Introduction to Computer Organization

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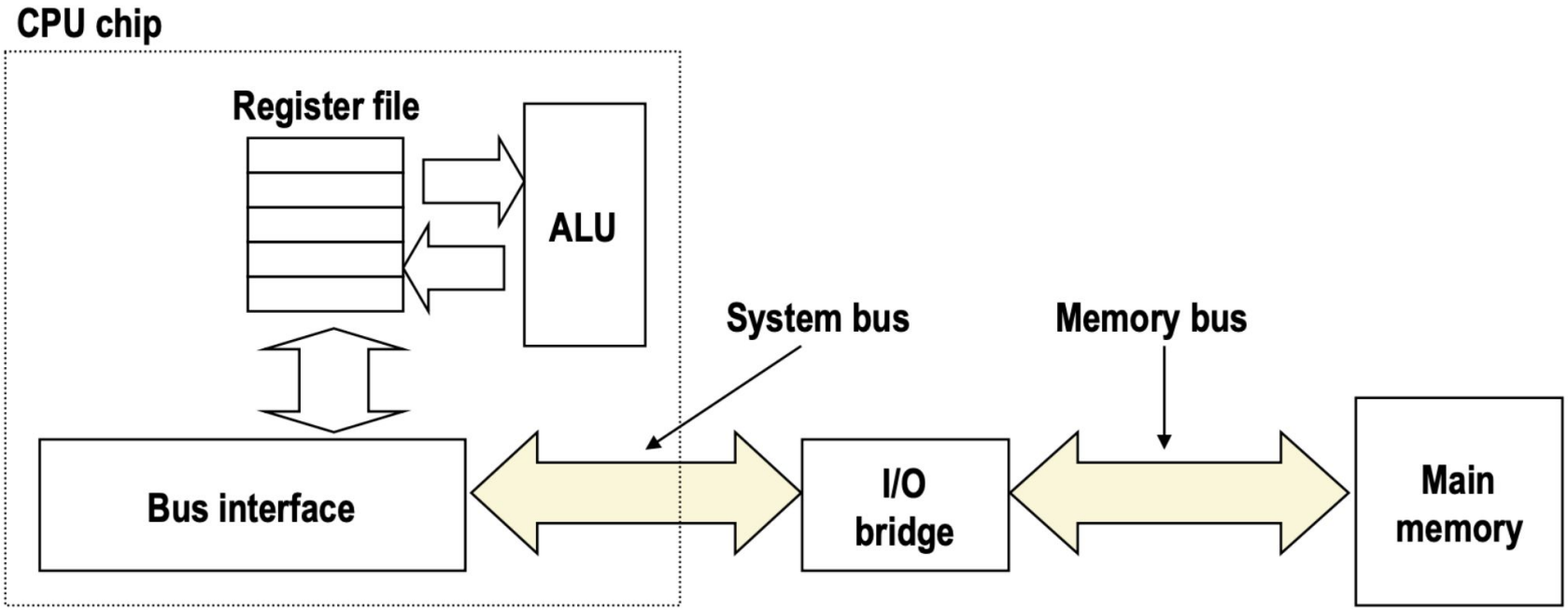
Office Hours: Friday, 9:30-11:30AM

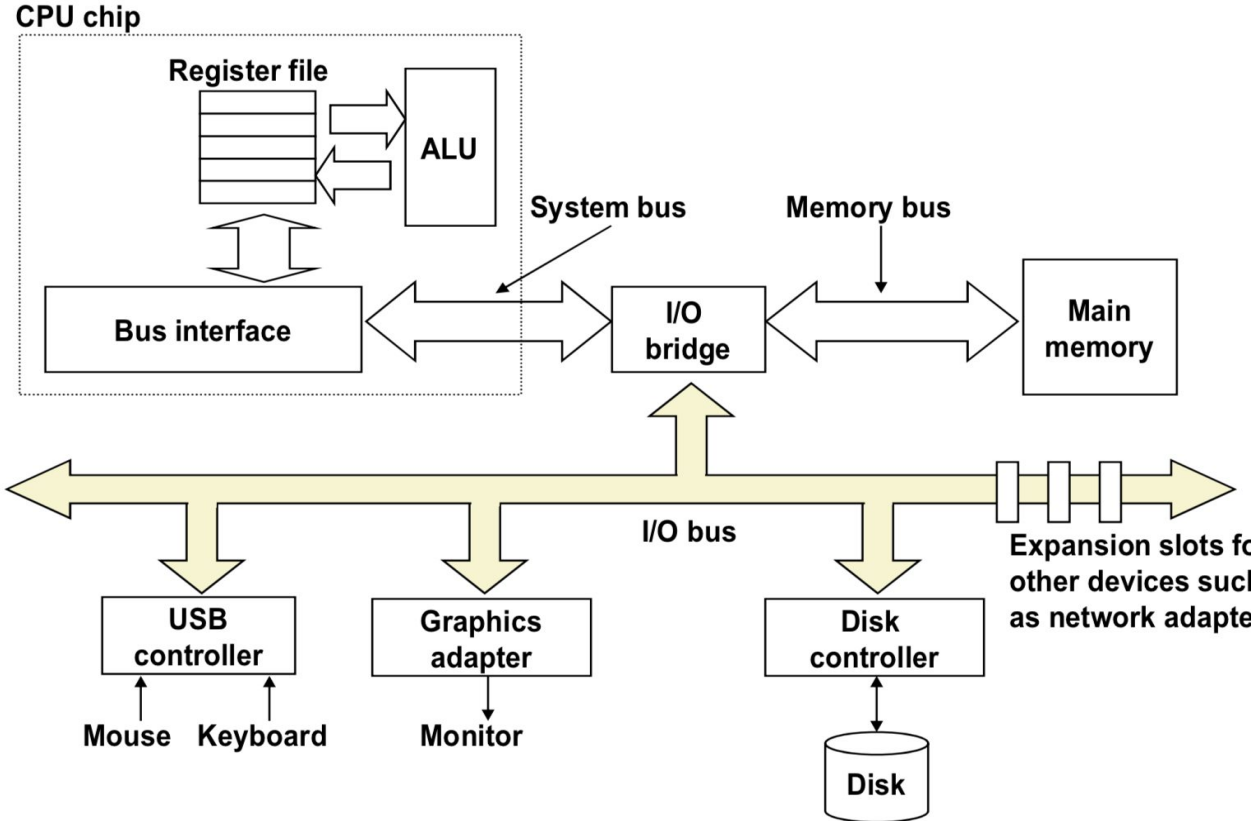
Outline

- **Memory Architecture**
- **Locality**
- **Caching**
- **Worksheet Problems**

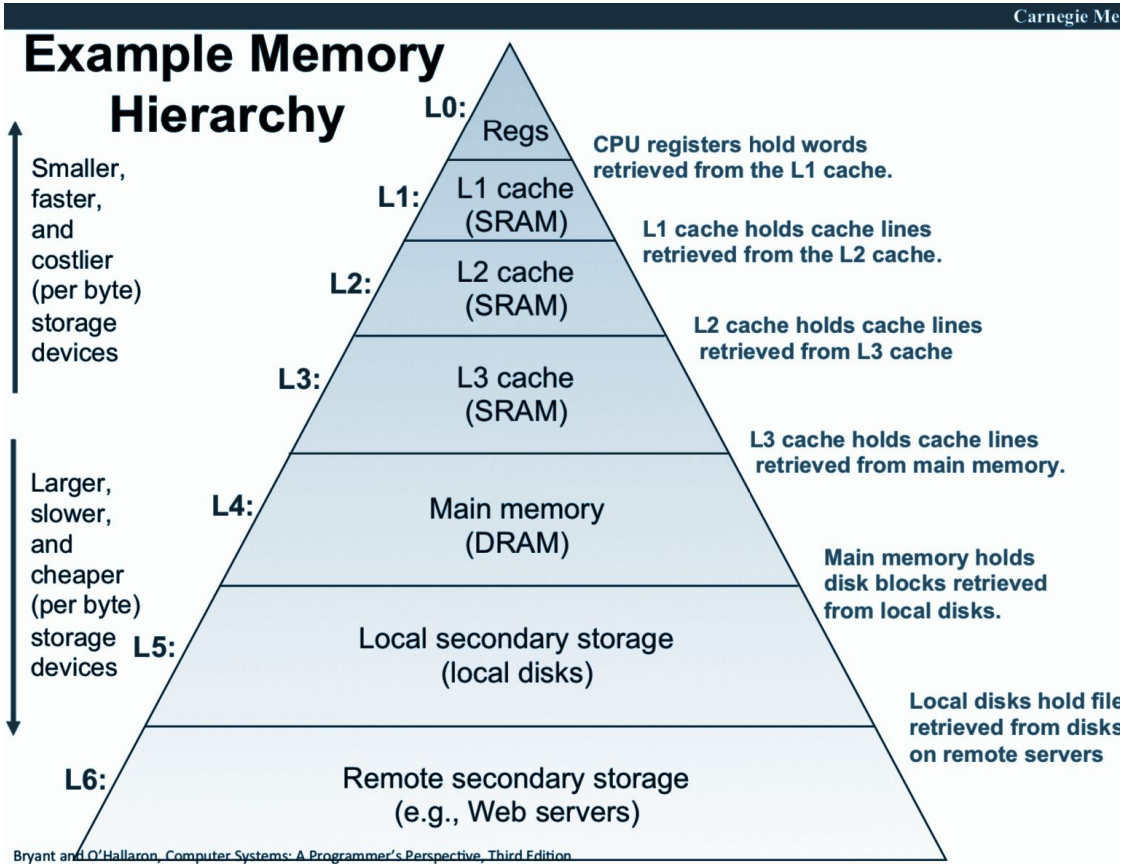
Memory and CPU Architecture



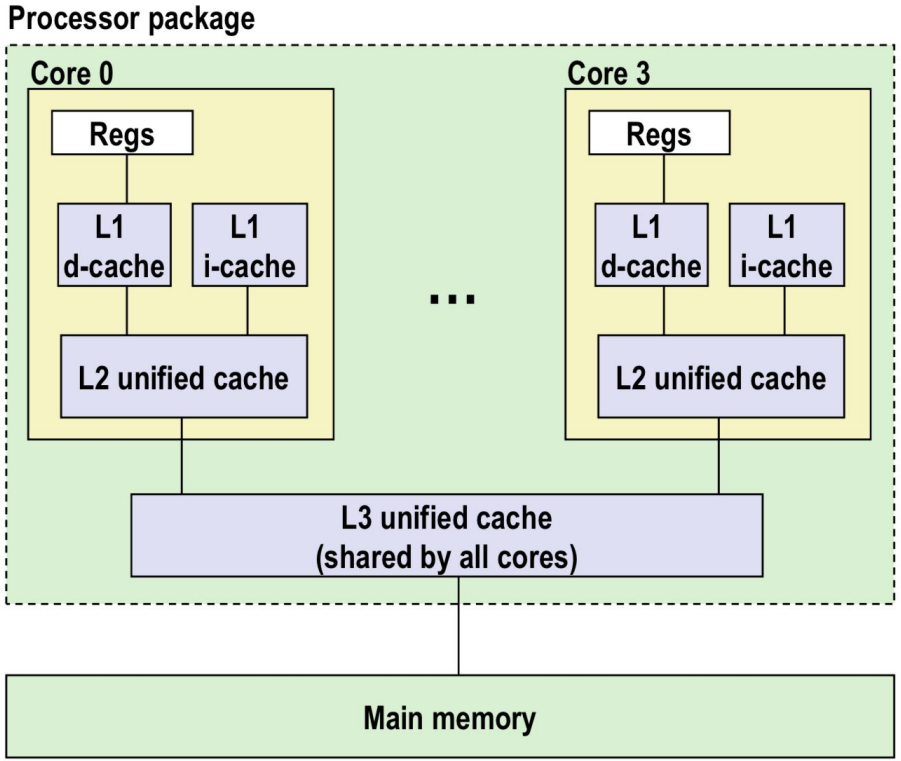
Memory and CPU Architecture - II



Memory Hierarchy



Cache Hierarchy



L1 i-cache and d-cache:
32 KB, 8-way,
Access: 4 cycles

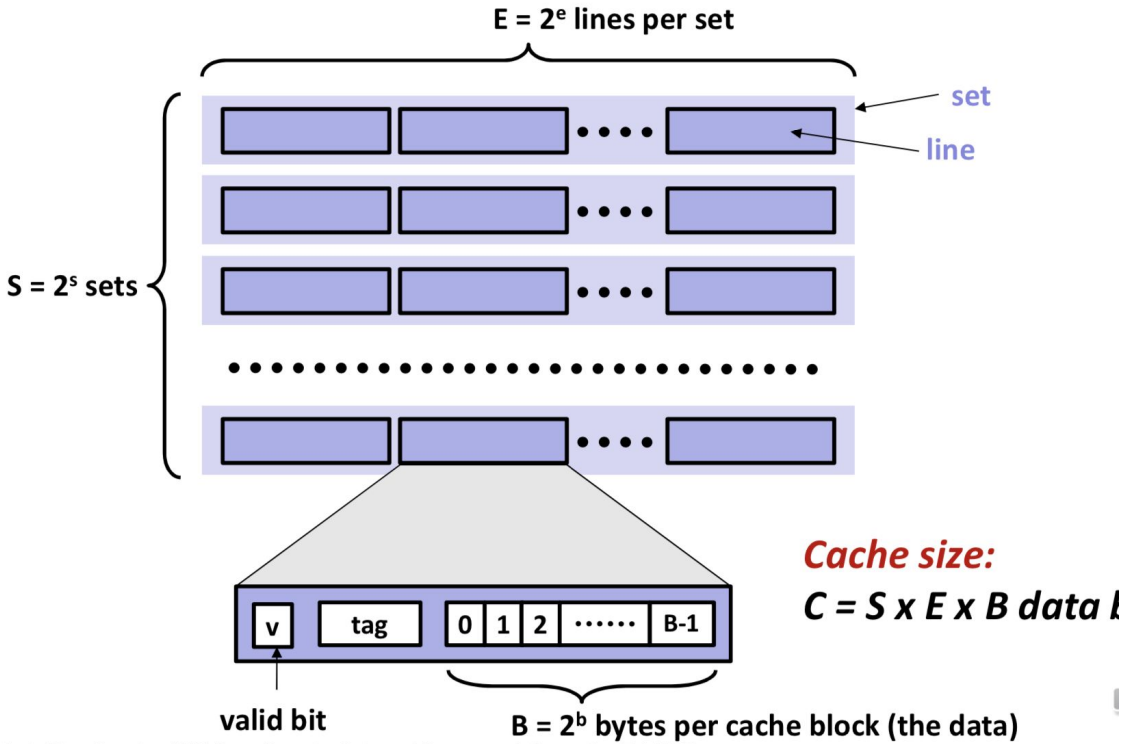
L2 unified cache:
256 KB, 8-way,
Access: 10 cycles

L3 unified cache:
8 MB, 16-way,
Access: 40-75 cycles

Block size: 64 bytes for all caches.

Hit-Rate?
Miss-Rate?

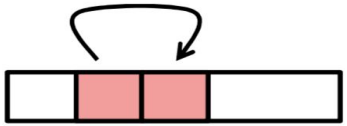
Cache Structure



Locality

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

Types of Locality



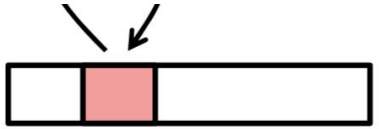
- **Spatial locality:**
  - Items with nearby addresses tend to be referenced close together in time

Example:

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

Types of Locality

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



Example:

```
for(i = 0; i < 20; i++)
    for(j = 0; j < 10; j++)
        a[i] = a[i]*j;
```

Question

```
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;
}
```

Does this function have good locality?

What can be done?

Source: http://www.cs.cmu.edu/afs/cs/academic/class/15213-s08/www/lectures/class10.pdf

Solution - Swap Loops

```
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;
}
```

One More Example - Let's Do it!

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

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

How can we improve the spatial locality?

One More Example - Let's Do it!

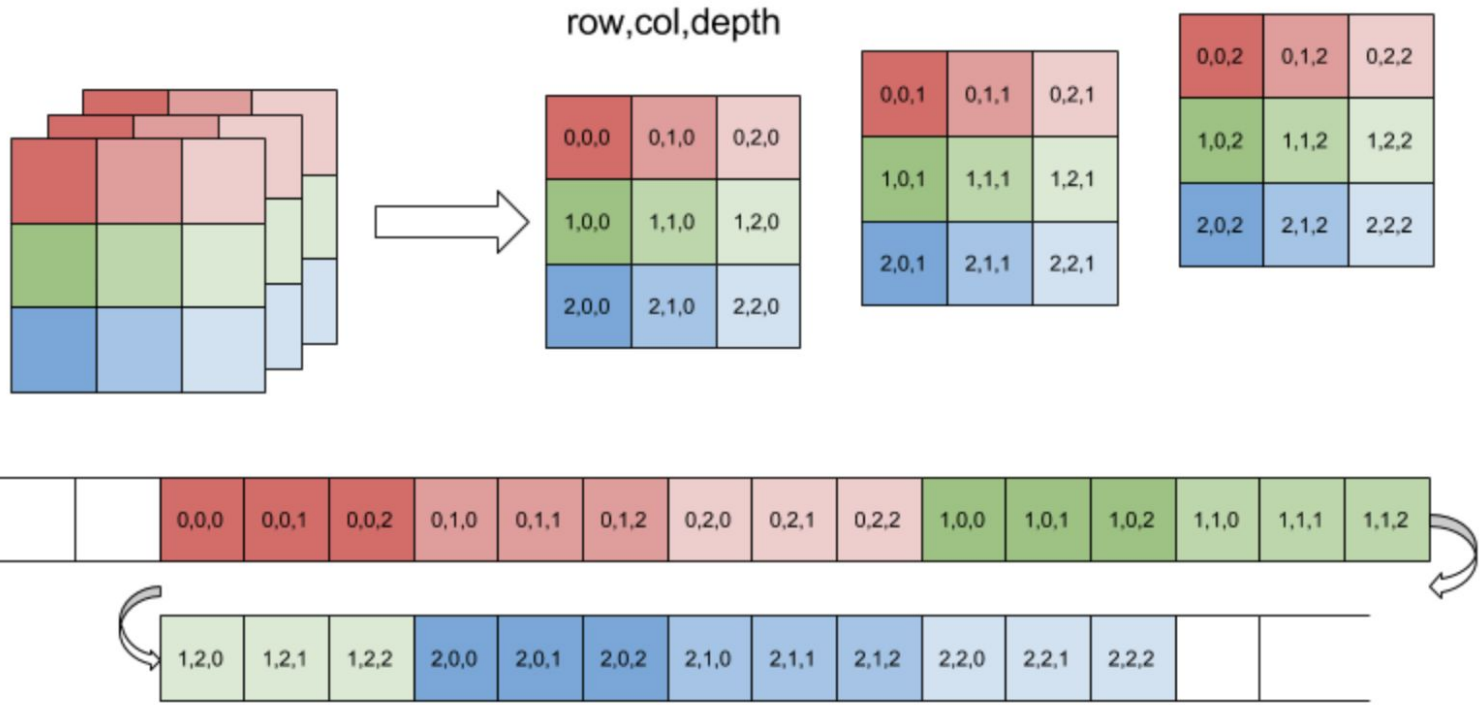
```
int sum_array_3d(int a[M][N][N])
{
    int i, j, k, sum = 0;

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

How can we improve the spatial locality?

Ordering: k, i, j

3D Array Representation

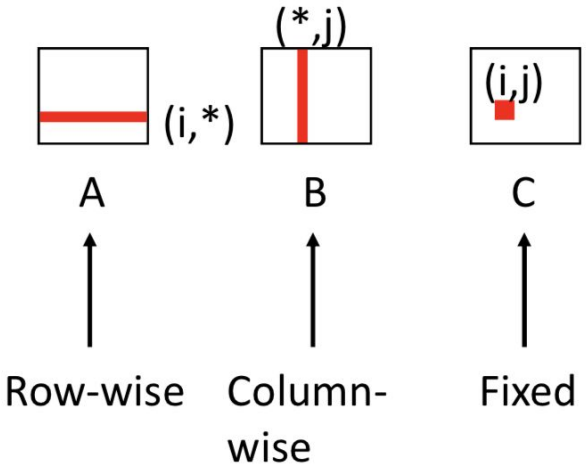


Matrix Multiplication

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

matmult/mm.c

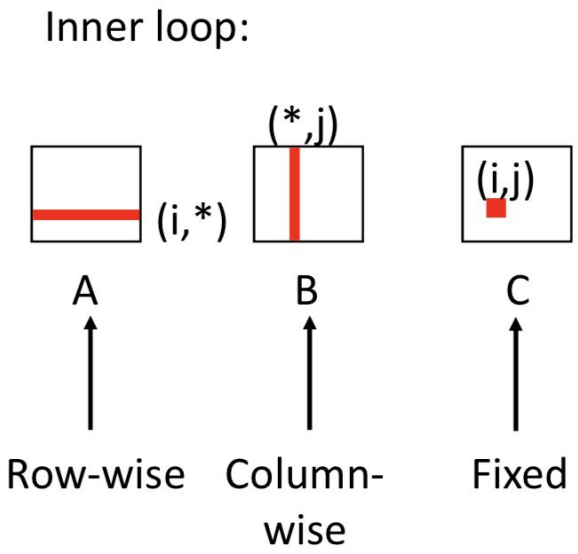
Inner loop:



Matrix Multiplication - Variation I

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

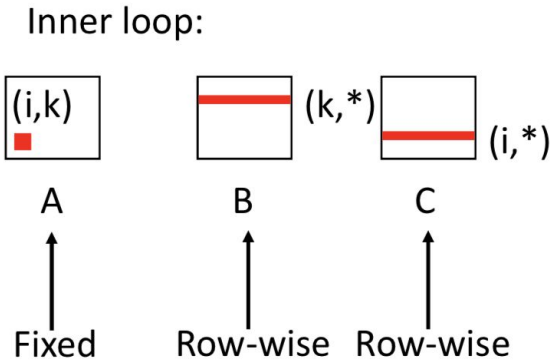
matmult/mm.c



Matrix Multiplication - Variation II

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

matmult/mm.c



Worksheet

https://tinyurl.com/cs33-mid-quarter-blues