CS 61C: Great Ideas in Computer Architecture (Machine Structures)
Thread-Level Parallelism (TLP) and OpenMP

Instructors:

Krste Asanovic & Vladimir Stojanovic

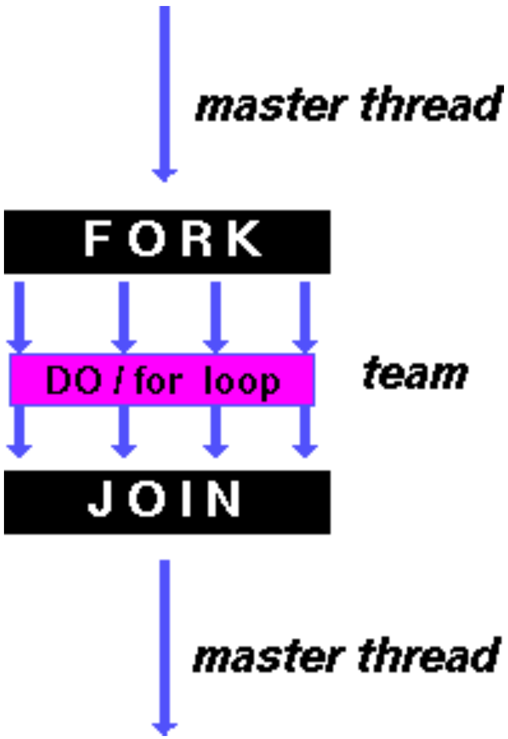
http://inst.eecs.berkeley.edu/~cs61c/

Review

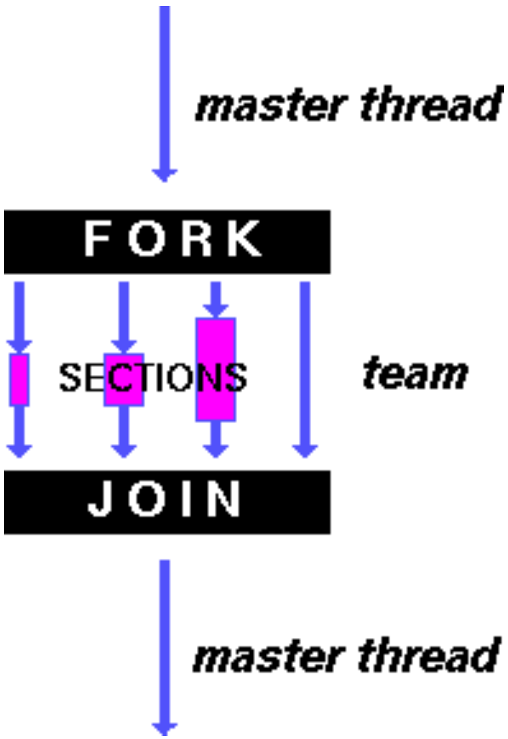
- Sequential software is slow software
  - SIMD and MIMD only path to higher performance
- Multithreading increases utilization, Multicore more processors (MIMD)
- Synchronization
  - atomic read-modify-write using load-linked/store-conditional
- OpenMP as simple parallel extension to C
  - Threads, Parallel for, private, critical sections, …
  - ≈ C: small so easy to learn, but not very high level and it's easy to get into trouble

OpenMP Directives (Work-Sharing)

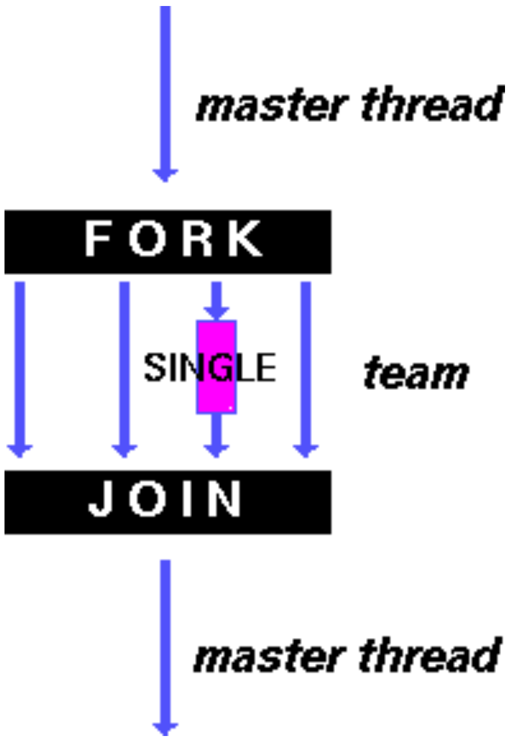
- These are defined *within* a `parallel` section



Shares iterations of a loop across the threads



Each section is executed by a separate thread



Serializes the execution of a thread

`Parallel` Statement Shorthand

```
#pragma omp parallel
{
  #pragma omp for
  for(i=0;i<len;i++) { … }
}
```

This is the only directive in the parallel section

can be shortened to:

```
#pragma omp parallel for
  for(i=0;i<len;i++) { … }
```

- Also works for `sections`

Building Block: `for` loop

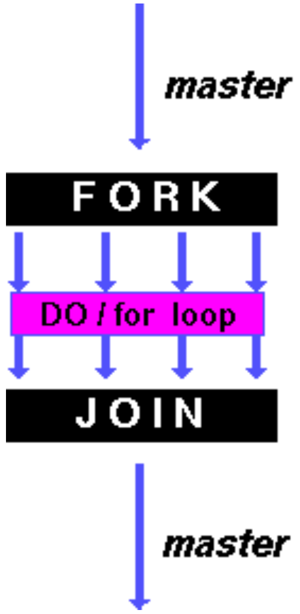
```
for (i=0; i<max; i++) zero[i] = 0;
```

- Break *for loop* into chunks, and allocate each chunk to a separate thread
  - e.g. if `max` = 100 with 2 threads:
    assign 0-49 to thread 0, and 50-99 to thread 1
- Must have relatively simple "shape" for an OpenMP-aware compiler to be able to parallelize it
  - Necessary for the run-time system to be able to determine how many of the loop iterations to assign to each thread
- No premature exits from the loop allowed
  - i.e. No `break`, `return`, `exit`, `goto` statements

In general, don't jump outside of any pragma block

Parallel `for` *pragma*

```
#pragma omp parallel for
   for (i=0; i<max; i++) zero[i] = 0;
```



- Master thread creates additional threads, each with a separate execution context
- All variables declared outside for loop are shared by default, except for loop index which is *private* per thread (Why?)
- Implicit synchronization at end of for loop
- Divide index regions sequentially per thread
  - Thread 0 gets 0, 1, …, (max/n)-1;
  - Thread 1 gets max/n, max/n+1, …, 2*(max/n)-1
  - Why?

OpenMP Timing

- Elapsed wall clock time:

```
double omp_get_wtime(void);
```

  - Returns elapsed wall clock time in seconds
  - Time is measured per thread, no guarantee can be made that two distinct threads measure the same time
  - Time is measured from "some time in the past," so subtract results of two calls to `omp_get_wtime` to get elapsed time

Matrix Multiply in OpenMP

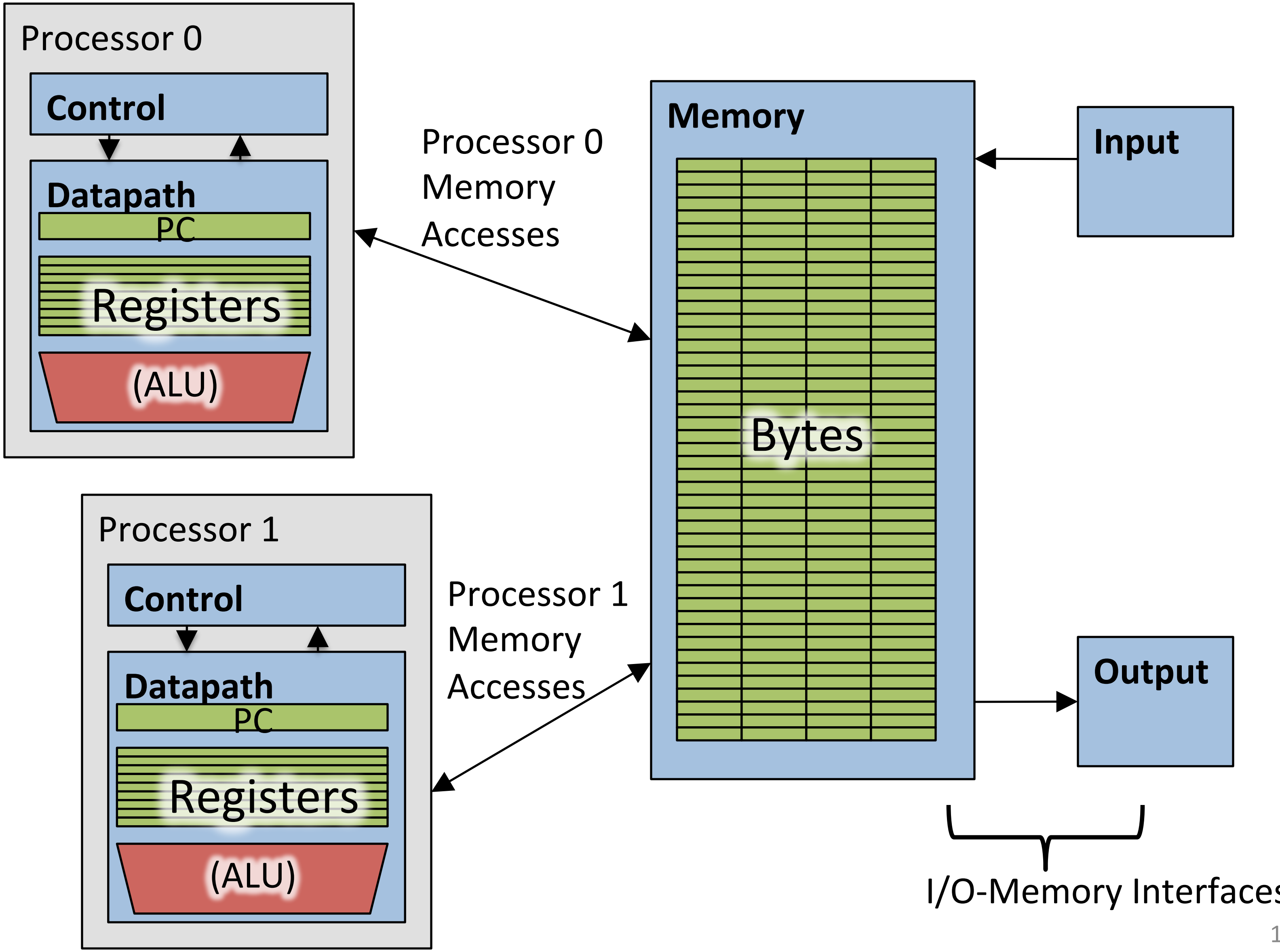
```
start_time = omp_get_wtime();
#pragma omp parallel for private(tmp, i, j, k)
  for (i=0; i<Mdim; i++){
    for (j=0; j<Ndim; j++){
      tmp = 0.0;
      for( k=0; k<Pdim; k++){
        /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
        tmp += *(A+(i*Pdim+k)) * *(B+(k*Ndim+j));
      }
      *(C+(i*Ndim+j)) = tmp;
    }
  }
run_time = omp_get_wtime() - start_time;
```

Outer loop spread across N threads; inner loops inside a single thread

Notes on Matrix Multiply Example

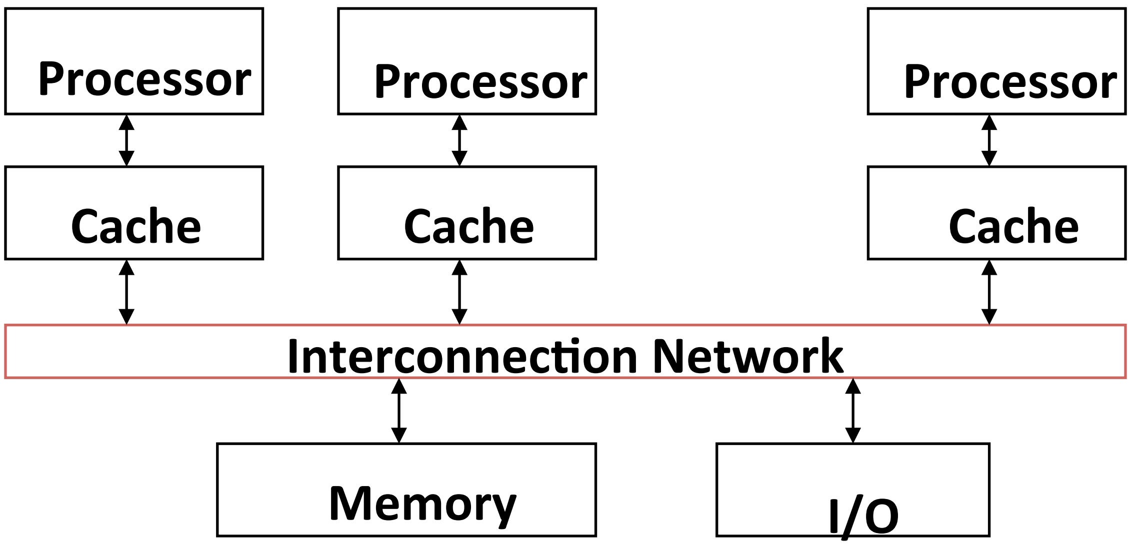
- More performance optimizations available:
  - Higher *compiler optimization* (-O2, -O3) to reduce number of instructions executed
  - *Cache blocking* to improve memory performance
  - Using SIMD SSE instructions to raise floating point computation rate (*DLP*)

Simple Multiprocessor



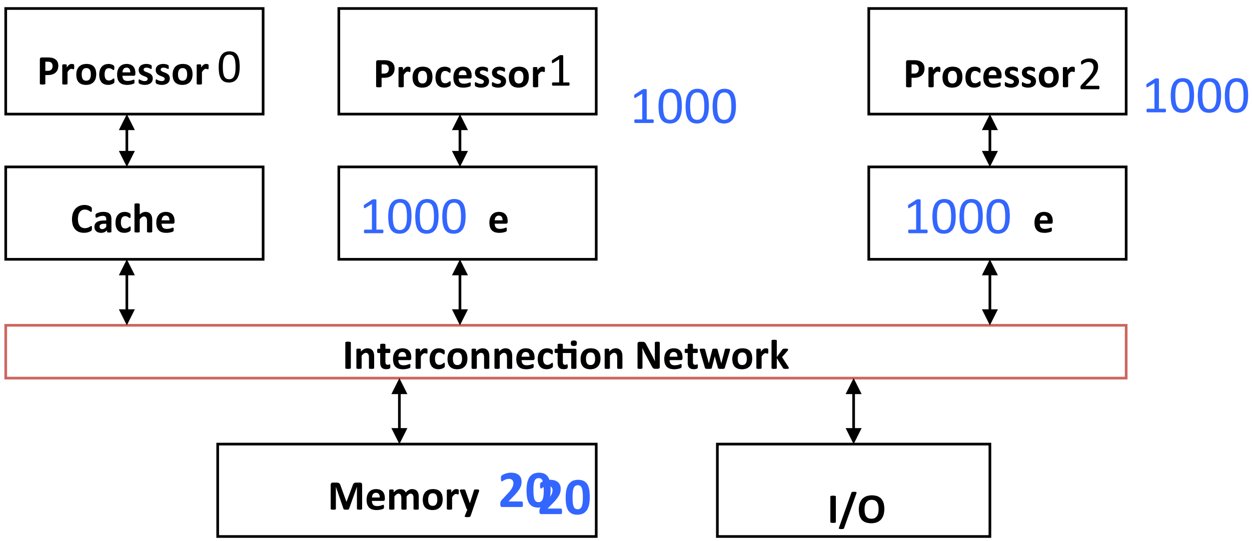
Multiprocessor Caches

- Memory is a performance bottleneck even with one processor
- Use caches to reduce bandwidth demands on main memory
- Each core has a local private cache holding data it has accessed recently
- Only cache misses have to access the shared common memory



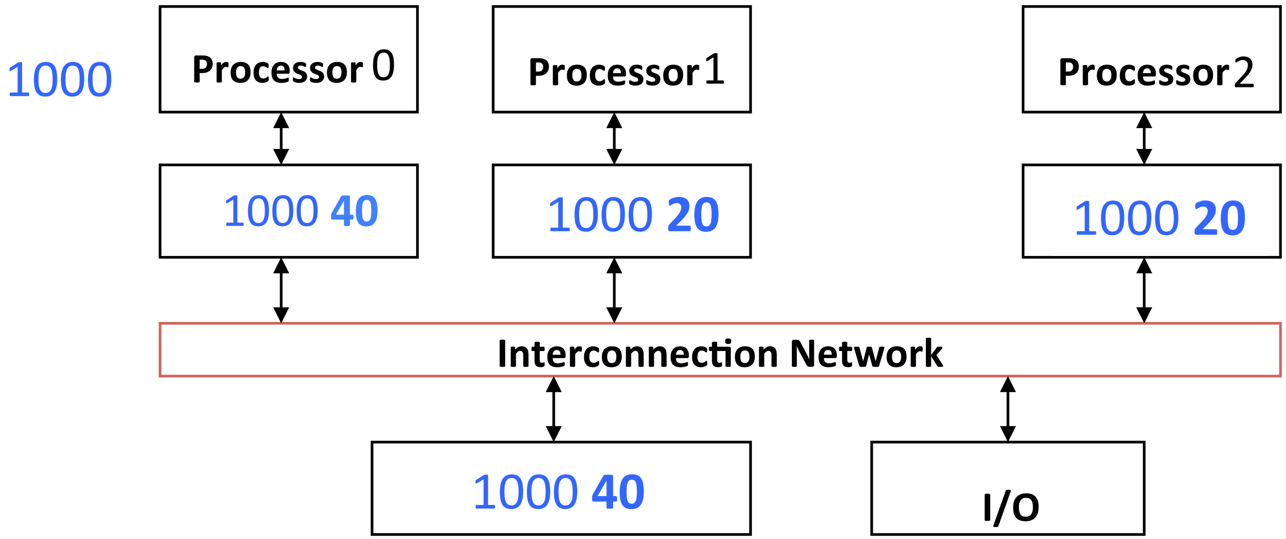
Shared Memory and Caches

- What if?
  – Processors 1 and 2 read Memory[1000] (value 20)



Shared Memory and Caches

- Now:
  - Processor 0 writes Memory[1000] with 40



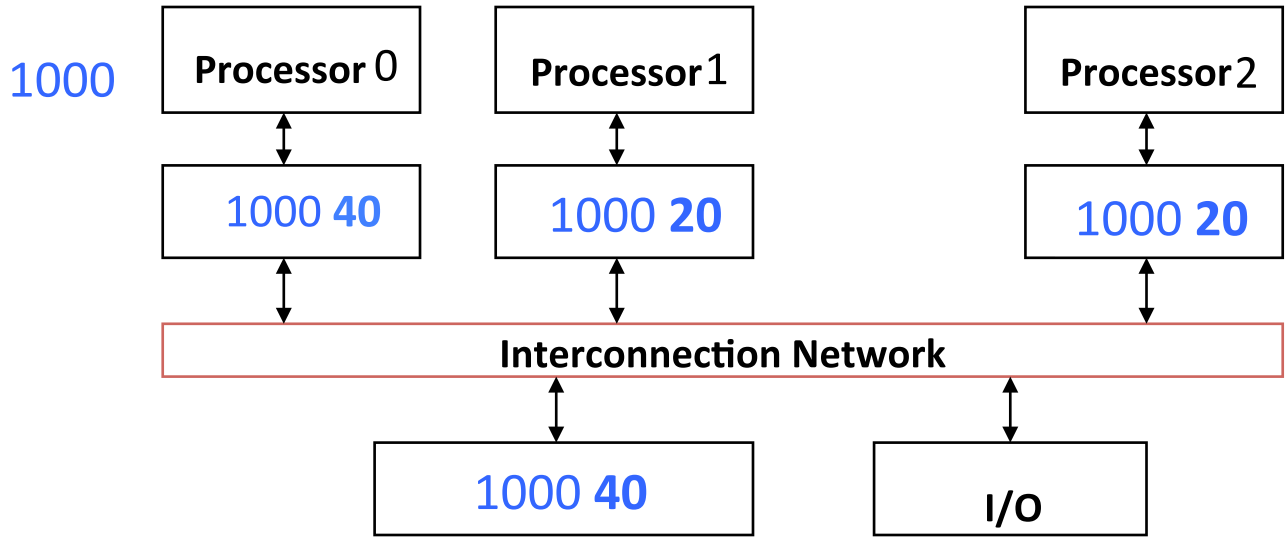
Problem?

Keeping Multiple Caches Coherent

- Architect's job: shared memory
  => keep cache values coherent
- Idea: When any processor has cache miss or writes, notify other processors via interconnection network
  - If only reading, many processors can have copies
  - If a processor writes, invalidate any other copies
- Write transactions from one processor "snoop" tags of other caches using common interconnect
  - Invalidate any "hits" to same address in other caches
  - If hit is to dirty line, other cache has to write back first!

Shared Memory and Caches

- Example, now with cache coherence
  - Processors 1 and 2 read Memory[1000]
  - Processor 0 writes Memory[1000] with 40



Processor 0 Write Invalidates Other Copies

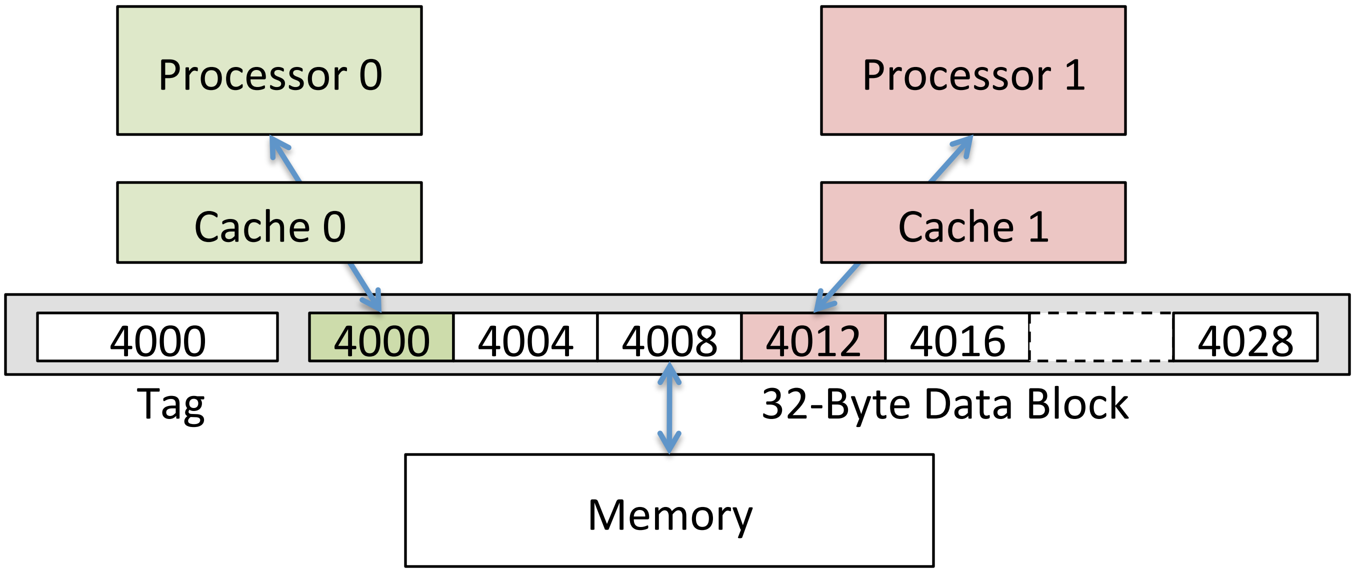
Clickers/Peer Instruction: Which statement is true?

- **A: Using write-through caches removes the need for cache coherence**
- **B: Every processor store instruction must check contents of other caches**
- **C: Most processor load and store accesses only need to check in local private cache**
- **D: Only one processor can cache any memory location at one time**

Administrivia

- MT2 is Thursday, April 9th:
  - Covers lecture material up till 3/31 lecture
  - TWO cheat sheets, 8.5"x11"

Cache Coherency Tracked by Block



- Suppose block size is 32 bytes
- Suppose Processor 0 reading and writing variable X, Processor 1 reading and writing variable Y
- Suppose in X location 4000, Y in 4012
- What will happen?

Coherency Tracked by Cache Line

- Block ping-pongs between two caches even though processors are accessing disjoint variables
- Effect called *false sharing*
- How can you prevent it?

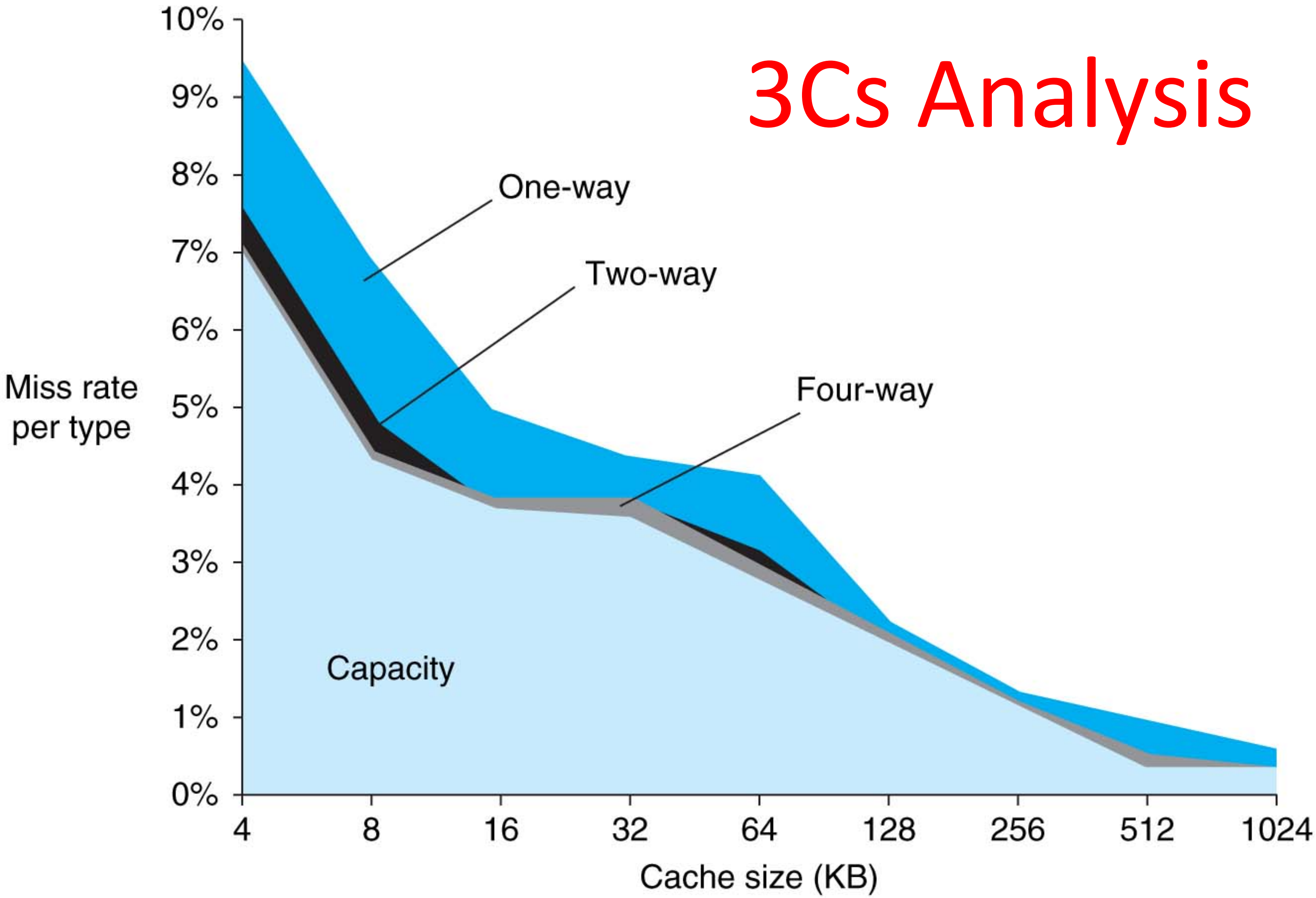
Review: Understanding Cache Misses: The 3Cs

- Compulsory (cold start or process migration, 1st reference):
  - First access to block, impossible to avoid; small effect for long-running programs
  - Solution: increase block size (increases miss penalty; very large blocks could increase miss rate)
- Capacity (not compulsory and…)
  - Cache cannot contain all blocks accessed by the program ***even with perfect replacement policy in fully associative cache***
  - Solution: increase cache size (may increase access time)
- Conflict (not compulsory or capacity and…):
  - Multiple memory locations map to the same cache location
  - Solution 1: increase cache size
  - Solution 2: increase associativity (may increase access time)
  - Solution 3: improve replacement policy, e.g.. LRU

How to Calculate 3C's using Cache Simulator

1. *Compulsory*: set cache size to infinity and fully associative, and count number of misses
2. *Capacity*: reduce cache size from infinity, usually in powers of 2, ***implement optimal replacement***, and count misses for each reduction in size
   – 16 MB, 8 MB, 4 MB, … 128 KB, 64 KB, 16 KB
3. *Conflict*: Change from fully associative to n-way set associative while counting misses
   – Fully associative, 16-way, 8-way, 4-way, 2-way, 1-way

3Cs Analysis



- Three sources of misses (SPEC2000 integer and floating-point benchmarks)
  - Compulsory misses 0.006%; not visible
  - Capacity misses, function of cache size
  - Conflict portion depends on associativity and cache size

Fourth "C" of Cache Misses: *Coherence* Misses

- Misses caused by coherence traffic with other processor
- Also known as *communication* misses because represents data moving between processors working together on a parallel program
- For some parallel programs, coherence misses can dominate total misses

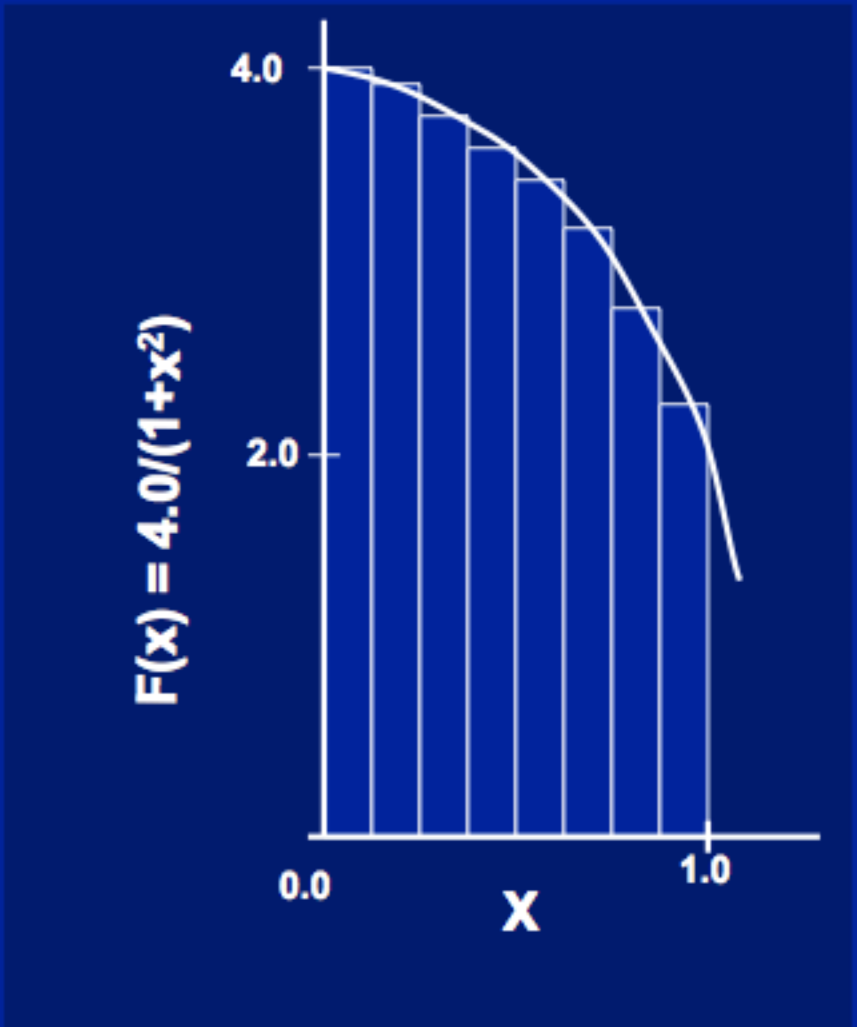
π

3.

141592653589793238462643383279502
884197169399375105820974944592307
816406286208998628034825342117067
982148086513282306647093844609550
582231725359408128481117450284102
...

Calculating π

Numerical Integration



Mathematically, we know that:

$$\int_0^1 \frac{4.0}{(1+x^2)}\,dx = \pi$$

We can approximate the integral as a sum of rectangles:

$$\sum_{i=0}^{N} F(x_i)\Delta x \approx \pi$$

Where each rectangle has width Δx and height $F(x_i)$ at the middle of interval i.

Sequential Calculation of π in C

```
#include <stdio.h>/* Serial Code */
static long num_steps = 100000; double step;
void main ()
{   int i;      double x, pi, sum = 0.0;
    step = 1.0/(double) num_steps;
    for (i=1;i<= num_steps; i++){
      x = (i-0.5)*step;
      sum = sum + 4.0/(1.0+x*x);
    }
    pi = sum/num_steps;
    printf ("pi = %6.12f\n", pi);
}
```

OpenMP Version (with bug)

```
#include <omp.h>
static long num_steps = 100000; double step;
#define NUM_THREADS 2
void main ()
{    int i;     double  x, pi, sum[NUM_THREADS];
     step = 1.0/(double) num_steps;
#pragma omp parallel private (x)
{    int id = omp_get_thread_num();
     for (i=id, sum[id]=0.0; i< num_steps; i=i+NUM_THREADS)
     {
         x = (i+0.5)*step;
         sum[id] += 4.0/(1.0+x*x);
      }
}
     for(i=0, pi=0.0; i<NUM_THREADS; i++)
       pi += sum[i] ;
   printf ("pi = %6.12f\n", pi  / num_steps);
}
```

Experiment

- Run with NUM_THREADS = 1 multiple times
- Run with NUM_THREADS = 2 multiple times
- What happens?

OpenMP Version (with bug)

```
#include <omp.h>
static long num_steps = 100000; double step;
#define NUM_THREADS 2
void main ()
{    int i;     double  x, pi, sum[NUM_THREADS];
     step = 1.0/(double) num_steps;
#pragma omp parallel private (x)
{    int id = omp_get_thread_num();
     for (i=id, sum[id]=0.0; i< num_steps; i=i+NUM_THREADS)
     {
        x = (i+0.5)*step;
        sum[id] += 4.0/(1.0+x*x);
     }
}
     for(i=0, pi=0.0; i<NUM_THREADS; i++)
       pi += sum[i] ;
   printf ("pi = %6.12f\n", pi/num_steps);
}
```

Note: loop index variable i is shared between threads

OpenMP Version 2 (with bug)

```
#include <omp.h>
static long num_steps = 100000; double step;
#define NUM_THREADS 2
void main ()
{    int i;     double  x, sum, pi=0.0;
     step = 1.0/(double) num_steps;
#pragma omp parallel private (x, sum)
{    int id = omp_get_thread_num();
     for (i=id, sum=0.0; i< num_steps; i=i+NUM_THREADS)
     {
         x = (i+0.5)*step;
         sum += 4.0/(1.0+x*x);
     }
#pragma omp critical
   pi += sum;
}
   printf ("pi = %6.12f\n",pi/num_steps);
}
```

OpenMP Reduction

- *Reduction*: specifies that 1 or more variables that are private to each thread are subject of reduction operation at end of parallel region: reduction(operation:var) where
  - *Operation*: operator to perform on the variables (var) at the end of the parallel region
  - *Var*: One or more variables on which to perform scalar reduction.

```
#pragma omp for reduction(+ : nSum)
  for (i = START ; i <= END ; ++i)
      nSum += i;
```

OpenMP Reduction Version

```
#include <omp.h>
#include <stdio.h>
/static long num_steps = 100000;
double step;
void main ()
{    int i;     double x, pi, sum = 0.0;
     step = 1.0/(double) num_steps;
#pragma omp parallel for private(x) reduction(+:sum)
     for (i=1; i<= num_steps; i++){
      x = (i-0.5)*step;
      sum = sum + 4.0/(1.0+x*x);
     }
     pi = sum / num_steps;
  printf ("pi = %6.8f\n", pi);
}
```

Note: Don't have to declare for loop index variable `i` private, since that is default

And in Conclusion, …

- Multiprocessor/Multicore uses Shared Memory
  - Cache coherency implements shared memory even with multiple copies in multiple caches
  - False sharing a concern; watch block size!
- OpenMP as simple parallel extension to C
  - Threads, Parallel for, private, critical sections, reductions …
  - ≈ C: small so easy to learn, but not very high level and it's easy to get into trouble