CS 110
Computer Architecture

OpenMP, Cache Coherence

Instructor:
Sören Schwertfeger

https://robotics.shanghaitech.edu.cn/courses/ca

School of Information Science and Technology SIST

ShanghaiTech University

Slides based on UC Berkley's CS61C

HW 5 fastest solution

Hash Distributed A*:

A Scalable Parallel Approach

Kaiyuan Xu

Bottleneck: Heap

- about one half of total runtime
- hard to parallelize

Solution

- using multiple heap

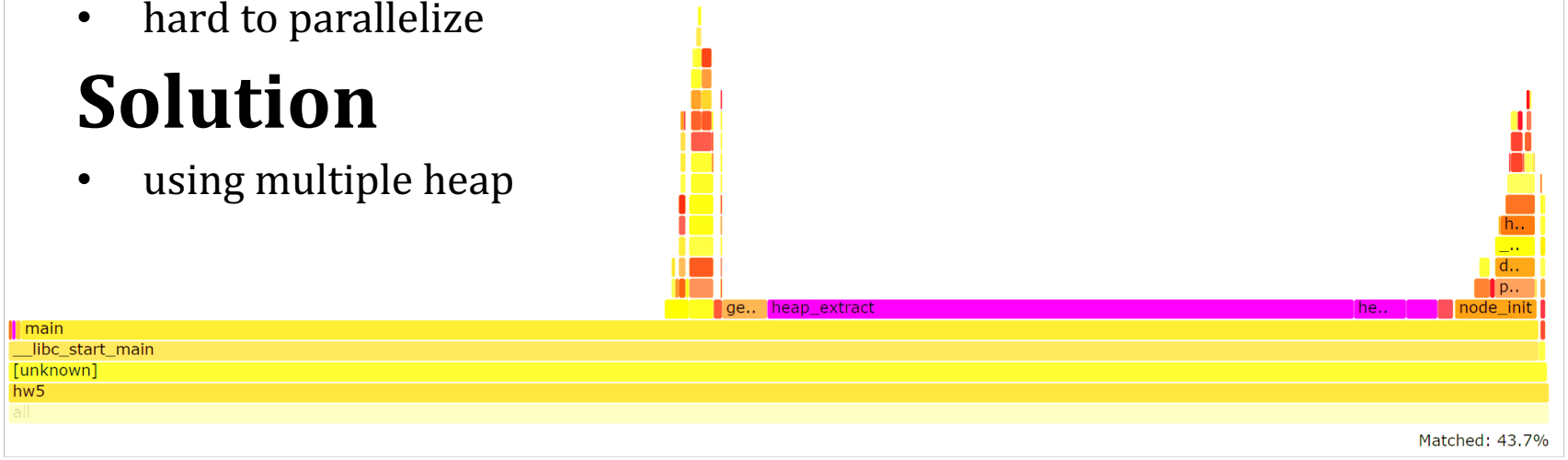


Figure 1:
time consumed on each part of one tread version of A* searching *maze-4821*
some optimization have been implemented
(created by *perf* and *Flame Graphs*)

Decentralizing

- every vertex is handled by one specific threads
- every thread has it's own heap and popping vertex from it
- inform corresponding threads to open adjacent vertices
- threads receive and send messages repeatedly

Problems and Overheads

- work division
- communicating between threads
- vertices reopening
- termination condition and detection

Dividing work: Hash

- mapping vertices to threads using hash function

Choosing Hash Function

- load balancing: randomness of hash function
- locality: mapping adjacent vertices to one thread could decreases the communication between threads but increases over searching

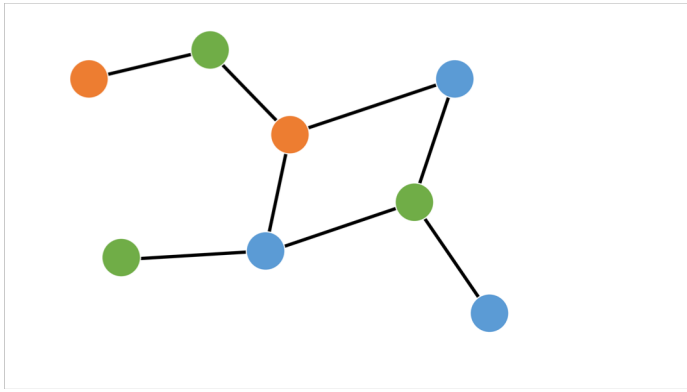


Figure 2 [1]: HDA* distributes work by hashing vertices to different processors. Hence this simple graph could distribute all vertices of a color to a particular processor.

Communication: Message Queue

- the primary overhead
- first in first out
- asynchronous sending and receiving
- multiple senders and one receiver
- implementation: linked list, array

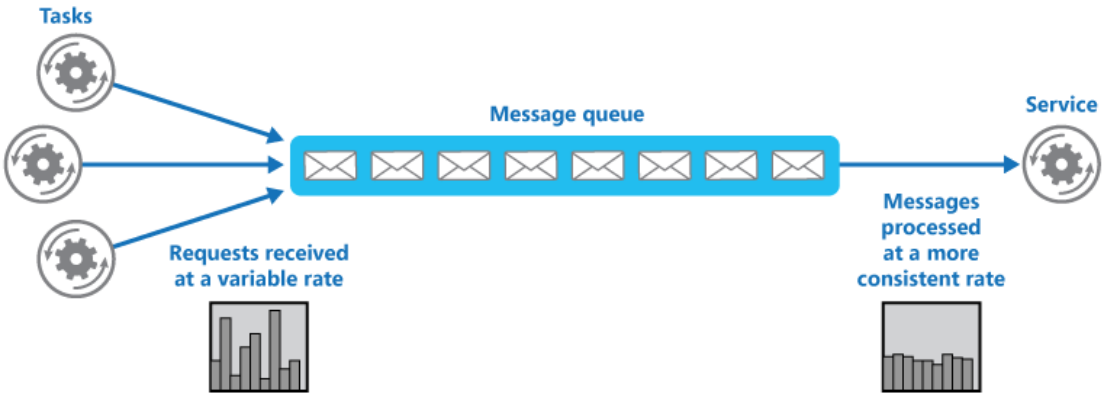


Figure 3:
a message queue used in a server
https://docs.microsoft.com/en-us/azure/architecture/patterns/queue-based-load-leveling

Termination condition

- popping the heap no longer gets the global minimum estimated (*fs*) vertices
- vertices may needed to be reopened when shorter *gs* found
- asynchronous message queue causing data inconsistency

Solution

- terminate once the estimated path length (*fs*) of all vertices in heap (in every threads) is longer than the shortest path found
- the detection is needed to be performed after no message is on sending, which is, every threads finished all local works

Termination detection

- problems with lock: performance, deadlock
- fabulous idea: when all the message is received, the termination is reached
- naively counting the number of message sent and received suffers from data inconsistency over time

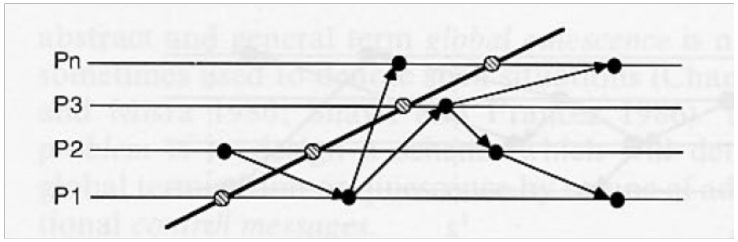


Figure 4 [2]:
data inconsistency over time

Solution

- still count sequentially, but count it in two rounds, first the message received, then the message sent

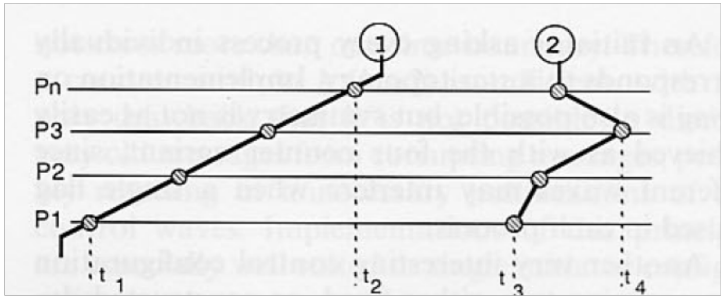


Figure 5 [2]:
two control wave method solves the problem

Implementation

- a mixture of bidirectional A* and HDA*
- simple hash function
- lock free linked list based asynchronous message queue
- memory pool instead of ptmallc
- 2x faster than bidirectional A*, should be better according to other's result [3]

Possible Causes

- hash function chosen increases communication overhead
- other bottleneck unnoticed
- different test cases

Reference and Acknowledgment

[1] Weinstock, Ariana, and Rachel Holladay. "Parallel A* Graph Search."

[2] Mattern, Friedemann. "Algorithms for distributed termination detection." Distributed computing 2.3 (1987): 161-175.

[3] Kishimoto, Akihiro, Alex Fukunaga, and Adi Botea. "Scalable, parallel best-first search for optimal sequential planning." Nineteenth International Conference on Automated Planning and Scheduling. 2009.

[4] Fukunaga, Alex, et al. "A Survey of Parallel A." arXiv preprint arXiv:1708.05296 (2017).

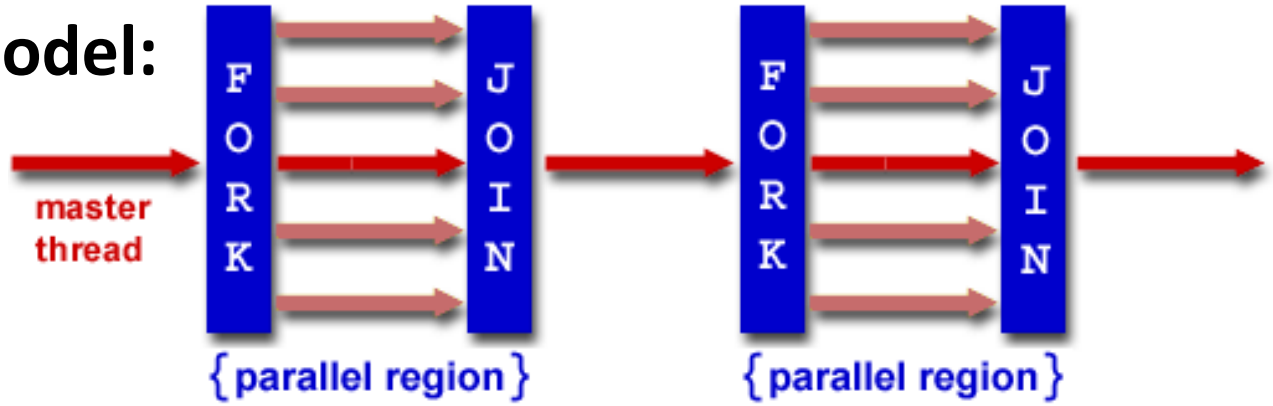
I appreciate schoolmate Jinrui Wang for sharing the he paper found and offering a better testing environment.

Review

- Sequential software is slow software
  - SIMD and MIMD are paths to higher performance
- MIMD thru: multithreading processor cores (increases utilization), Multicore processors (more cores per chip)
- Synchronization – coordination among threads
  - MIPS: atomic read-modify-write using load-linked/store-conditional
- OpenMP as simple parallel extension to C
  - Pragmas for forking multiple Threads
  - ≈ C: small so easy to learn, but not very high level and it's easy to get into trouble

OpenMP Programming Model - Review

- **Fork - Join Model:**



- OpenMP programs begin as single process (*master thread*) and executes sequentially until the first parallel region construct is encountered
  - *FORK:* Master thread then creates a team of parallel threads
  - Statements in program that are enclosed by the parallel region construct are executed in parallel among the various threads
  - *JOIN:* When the team threads complete the statements in the parallel region construct, they synchronize and terminate, leaving only the master thread

`parallel` Pragma and Scope - Review

- Basic OpenMP construct for parallelization:

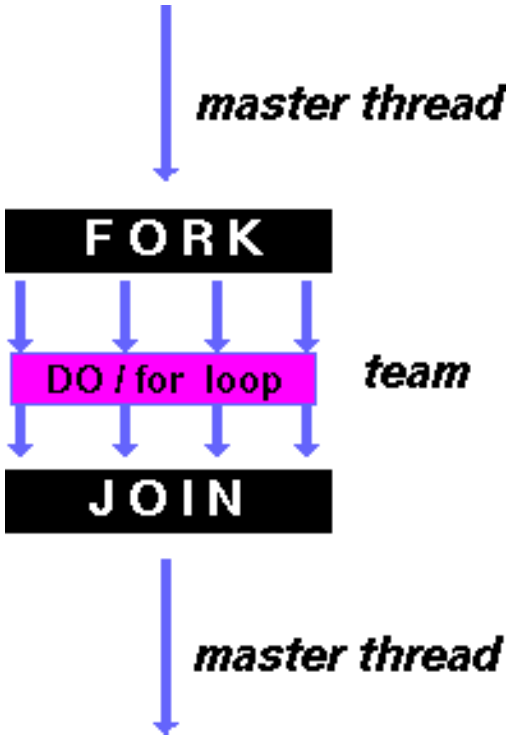
```
#pragma omp parallel
{
   /* code goes here */
}
```

  - *Each* thread runs a copy of code within the block
  - Thread scheduling is *non-deterministic*
- OpenMP default is *shared* variables
  - To make private, need to declare with pragma:

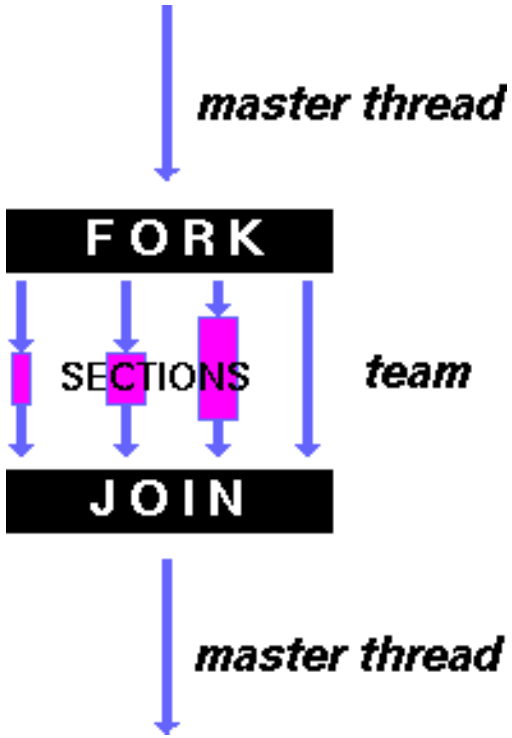
```
#pragma omp parallel private (x)
```

OpenMP Directives (Work-Sharing)

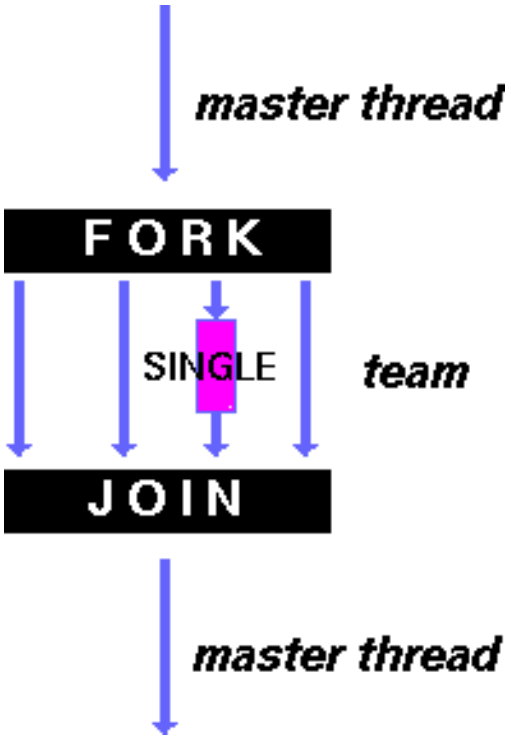
- These are defined *within* a `parallel` section



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

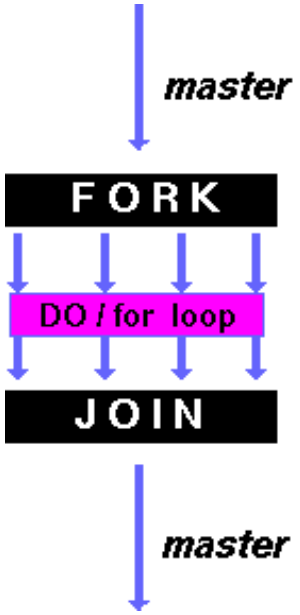
```
for (i=0; i<max; i++) zero[i] = 0;
```

- Breaks *for loop* into chunks, and allocate each 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 ← In general, don't jump outside of any pragma block
  - i.e. No `break`, `return`, `exit`, `goto` statements

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 "barrier" 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 Example

```c
/* clang -Xpreprocessor -fopenmp -lomp -o for for.c */

#include <stdio.h>
#include <omp.h>
int main()
{
    omp_set_num_threads(4);
    int a[] = { 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 };
    int N = sizeof(a)/sizeof(int);

    #pragma omp parallel for
    for (int i=0; i<N; i++) {
        printf("thread %d, i = %2d\n",
            omp_get_thread_num(), i);
        a[i] = a[i] + 10 * omp_get_thread_num();
    }

    for (int i=0; i<N; i++) printf("%02d ", a[i]);
    printf("\n");
}
```

```
$ gcc-5 -fopenmp for.c;./a.out
% clang -Xpreprocessor -fopenmp -
lomp -o for for.c; ./for
thread 0, i =  0
thread 1, i =  3
thread 2, i =  6
thread 3, i =  8
thread 0, i =  1
thread 1, i =  4
thread 2, i =  7
thread 3, i =  9
thread 0, i =  2
thread 1, i =  5
00 01 02 13 14 15 26 27 38 39
```


The call to find the maximum number of threads that are available to do work is **`omp_get_max_threads()`** (from omp.h).

OpenMP Timing

- Elapsed wall clock time:

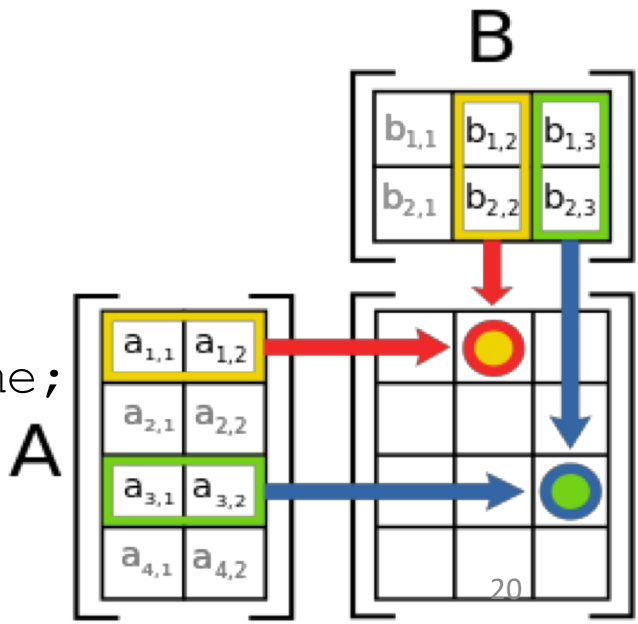
```
double omp_get_wtime(void);
```

  - 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

```
// C[M][N] = A[M][P] × B[P][N]
start_time = omp_get_wtime();
#pragma omp parallel for private(tmp, j, k)
  for (i=0; i<M; i++){
    for (j=0; j<N; j++){
      tmp = 0.0;
      for( k=0; k<P; k++){
        /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
        tmp += A[i][k] * B[k][j];
      }
      C[i][j] = tmp;
    }
  }
run_time = omp_get_wtime() - start_time;
```

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

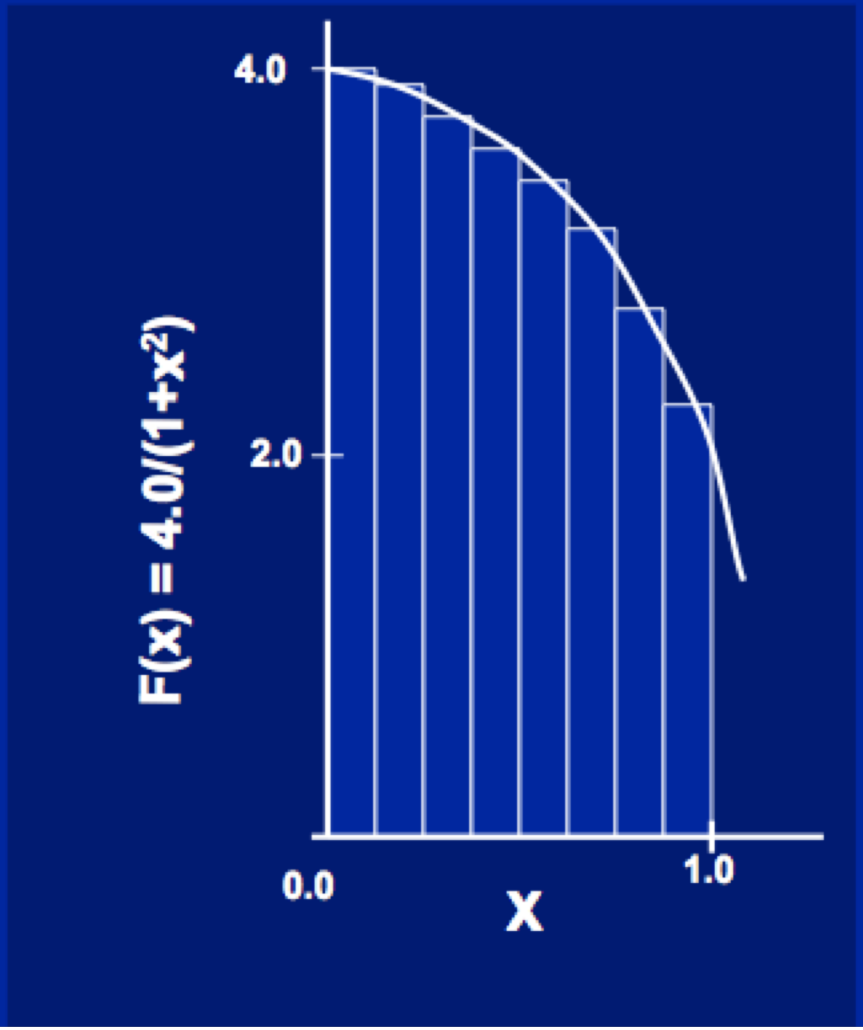


Notes on Matrix Multiply Example

- 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*)

Example: 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 π

```
#include <stdio.h>

void main () {
    const long num_steps = 10;
    double step = 1.0/((double)num_steps);
    double sum = 0.0;
    for (int i=0; i<num_steps; i++) {
        double x = (i+0.5) *step;
        sum += 4.0*step/(1.0+x*x);
    }
    printf ("pi = %6.12f\n", sum);
}
```

```
pi = 3.142425985001
```

- Resembles π, but not very accurate
- Let's increase **num_steps** and parallelize

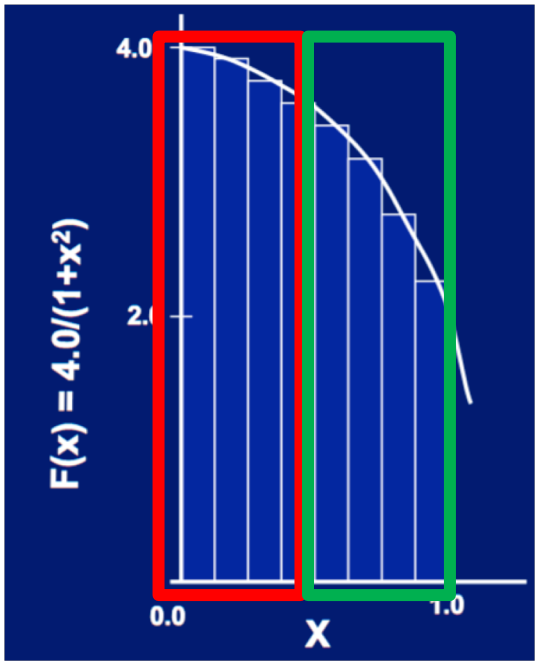
Parallelize (1) …

```
#include <stdio.h>

void main () {
    const long num_steps = 10;
    double step = 1.0/((double)num_steps);
    double sum = 0.0;
#pragma parallel for
    for (int i=0; i<num_steps; i++) {
        double x = (i+0.5) *step;
        sum += 4.0*step/(1.0+x*x);
    }
    printf ("pi = %6.12f\n", sum);
}
```

- Problem: each thread needs access to the shared variable **sum**
- Code runs sequentially …

Parallelize (2) …



1. Compute
   `sum[0]` and **`sum[1]`**
   in parallel

2. Compute
   `sum = sum[0] + sum[1]`
   sequentially

Parallel π … Trial Run

```
#include <stdio.h>
#include <omp.h>

void main () {
    const int NUM_THREADS = 4;
    const long num_steps = 10;
    double step = 1.0/((double)num_steps);
    double sum[NUM_THREADS];
    for (int i=0; i<NUM_THREADS; i++) sum[i] = 0;
    omp_set_num_threads(NUM_THREADS);
#pragma omp parallel
    {
        int id = omp_get_thread_num();
        for (int i=id; i<num_steps; i+=NUM_THREADS) {
            double x = (i+0.5) *step;
            sum[id] += 4.0*step/(1.0+x*x);
            printf("i =%3d,  id =%3d\n", i, id);
        }
    }
    double pi = 0;
    for (int i=0; i<NUM_THREADS; i++) pi += sum[i];
    printf ("pi = %6.12f\n", pi);
}
```

```
i =   1,   id =   1
i =   0,   id =   0
i =   2,   id =   2
i =   3,   id =   3
i =   5,   id =   1
i =   4,   id =   0
i =   6,   id =   2
i =   7,   id =   3
i =   9,   id =   1
i =   8,   id =   0
pi = 3.142425985001
```

Scale up: num_steps = 10^6

```
#include <stdio.h>
#include <omp.h>

void main () {
    const int NUM_THREADS = 4;
    const long num_steps = 1000000;
    double step = 1.0/((double)num_steps);
    double sum[NUM_THREADS];
    for (int i=0; i<NUM_THREADS; i++) sum[i] = 0;
    omp_set_num_threads(NUM_THREADS);
#pragma omp parallel
    {
        int id = omp_get_thread_num();
        for (int i=id; i<num_steps; i+=NUM_THREADS) {
            double x = (i+0.5) *step;
            sum[id] += 4.0*step/(1.0+x*x);
            // printf("i =%3d,  id =%3d\n", i, id);
        }
    }
    double pi = 0;
    for (int i=0; i<NUM_THREADS; i++) pi += sum[i];
    printf ("pi = %6.12f\n", pi);
}
```

pi = 3.141592653590

You verify how many digits are correct …

Can We Parallelize Computing sum?

```
#include <stdio.h>
#include <omp.h>

void main () {
    const int NUM_THREADS = 1000;
    const long num_steps = 100000;
    double step = 1.0/((double)num_steps);
    double sum[NUM_THREADS];
    for (int i=0; i<NUM_THREADS; i++) sum[i] = 0;
    double pi = 0;
    omp_set_num_threads(NUM_THREADS);
#pragma omp parallel
    {
        int id = omp_get_thread_num();
        for (int i=id; i<num_steps; i+=NUM_THREADS) {
            double x = (i+0.5) *step;
            sum[id] += 4.0*step/(1.0+x*x);
        }
        pi += sum[id];
    }
    printf ("pi = %6.12f\n", pi);
}
```

Always looking for ways to beat Amdahl's Law …

Summation inside parallel section

- Insignificant speedup in this example, but …
- **`pi = 3.138450662641`**
- Wrong! And value changes between runs?!
- What's going on?

Question

What are the possible values of **`*(x1)`** after executing this code by two ***concurrent*** threads?

```
# *(x1) = 100
lw   x2,0(x1)
addi x2,x2,1
sw   x2,0(x1)
```

Values of *(x1)?
A: None of these
B: 100
C: 101
D: 102
E: 100 or 101
F: 101 or 102
G: 100 or 102
H: 100 or 101 or 102

Question

What are the possible values of `*(x1)` after executing this code by two ***concurrent*** threads?

```
# *(x1) = 100
lw   x2,0(x1)
addi x2,x2,1
sw   x2,0(x1)
```

Values of *(x1)?
A: None of these
B: 100
C: 101
D: 102
E: 100 or 101
F: 101 or 102
G: 100 or 102
H: 100 or 101 or 102

If executed serially: 100→101→102

If both read 100, then both write 101

What's Going On?

```
#include <stdio.h>
#include <omp.h>

void main () {
    const int NUM_THREADS = 1000;
    const long num_steps = 100000;
    double step = 1.0/((double)num_steps);
    double sum[NUM_THREADS];
    for (int i=0; i<NUM_THREADS; i++) sum[i] = 0;
    double pi = 0;
    omp_set_num_threads(NUM_THREADS);
#pragma omp parallel
    {
        int id = omp_get_thread_num();
        for (int i=id; i<num_steps; i+=NUM_THREADS) {
            double x = (i+0.5) *step;
            sum[id] += 4.0*step/(1.0+x*x);
        }
        pi += sum[id];
    }
    printf ("pi = %6.12f\n", pi);
}
```

- Operation is really

  `pi = pi + sum[id]`
- What if >1 threads reads current (same) value of **`pi`**, computes the sum, stores the result back to **`pi`**?
- Each processor reads same intermediate value of **`pi`**!
- Result depends on who gets there when
  - A "race" → result is **not deterministic**

OpenMP Reduction

```
double avg, sum=0.0, A[MAX]; int i;
#pragma omp parallel for private ( sum )
for (i = 0; i <= MAX ; i++)
    sum += A[i];
avg = sum/MAX;  // bug
```

- *Problem is that we really want sum over all threads!*
- *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 : +, *, -, &, ^, |, &&, or ||.
  - *Var*: One or more variables on which to perform scalar reduction.

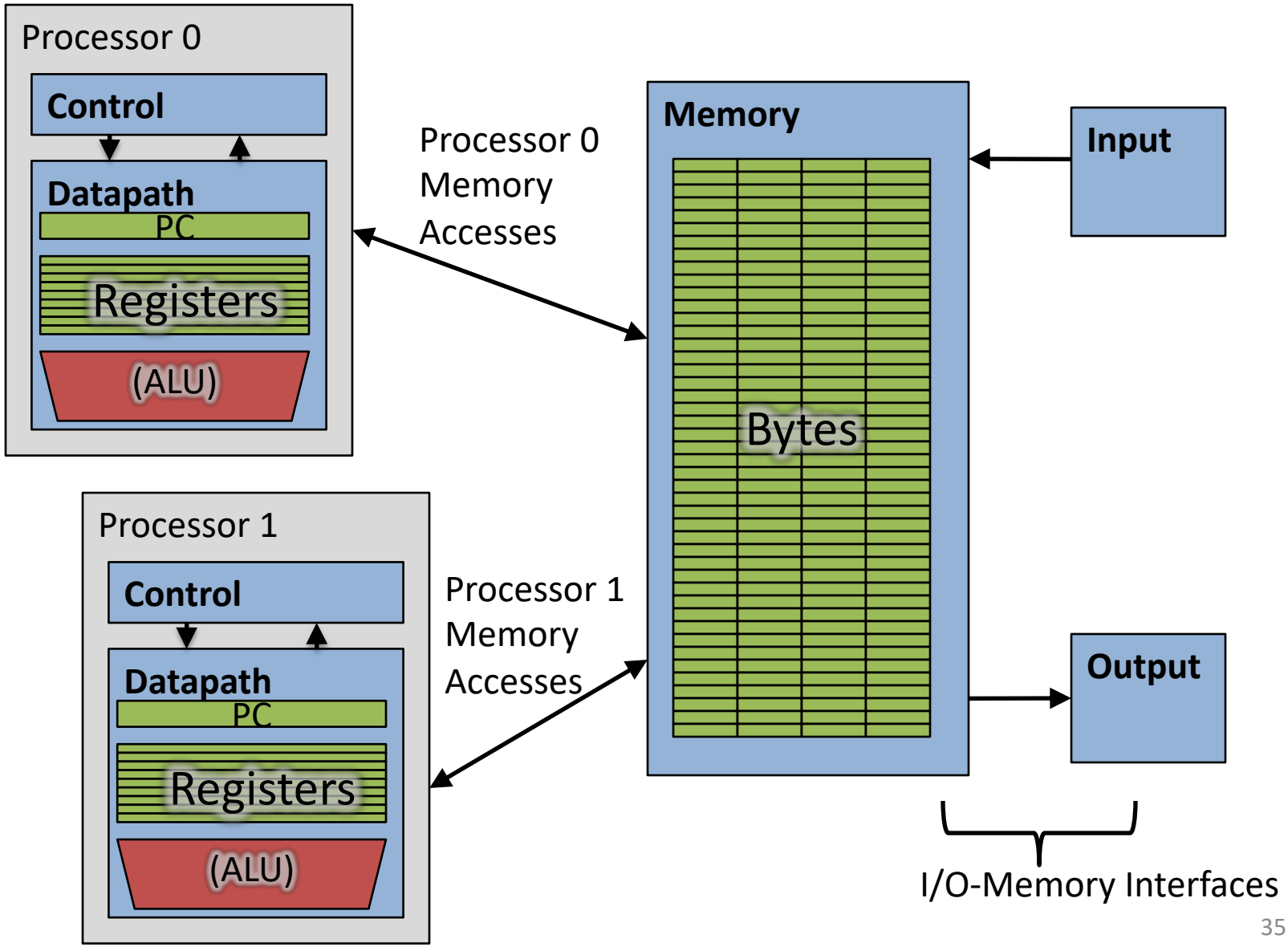
```
double avg, sum=0.0, A[MAX]; int i;
#pragma omp for reduction(+ : sum)
for (i = 0; i <= MAX ; i++)
    sum += A[i];
avg = sum/MAX;
```

parallel for, reduction

```
#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 * step;
     printf ("pi = %6.8f\n", pi);
}
```

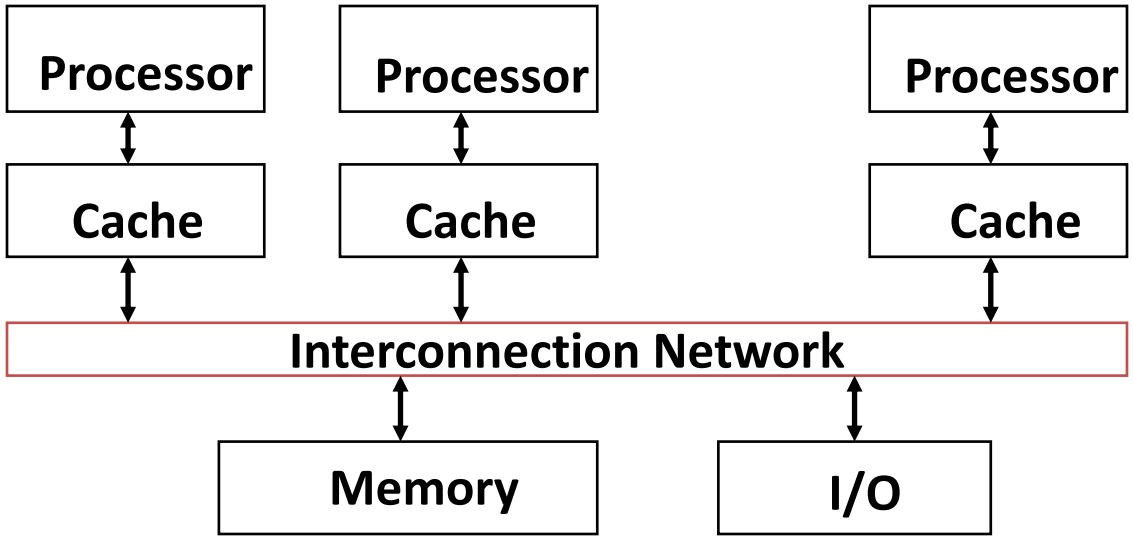
CACHE COHERENCE

Simple Multi-core Processor



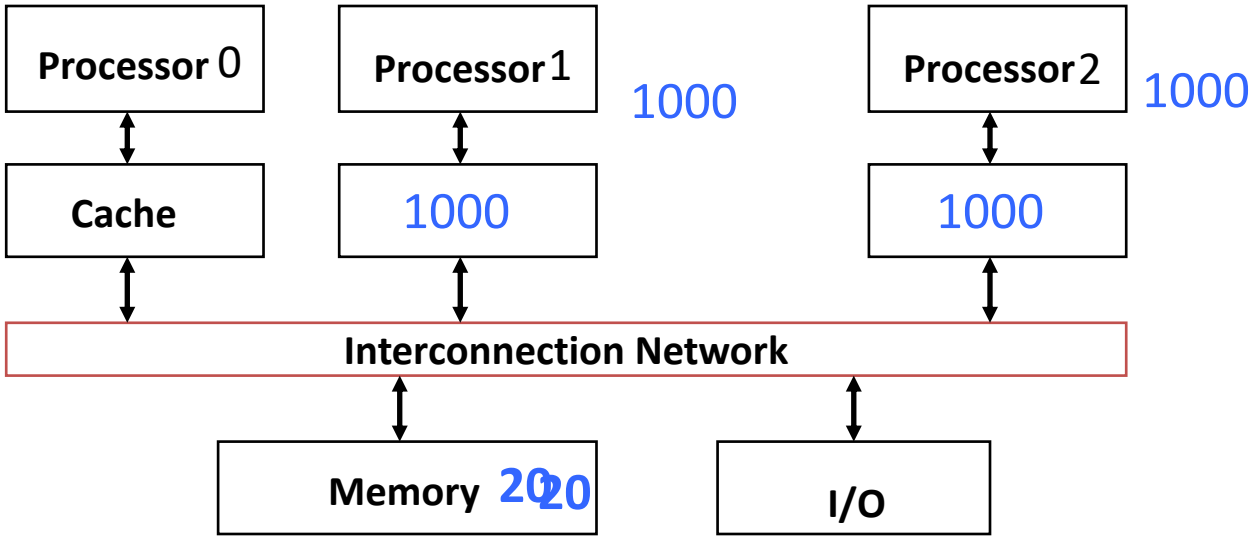
Multiprocessor Caches

- 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



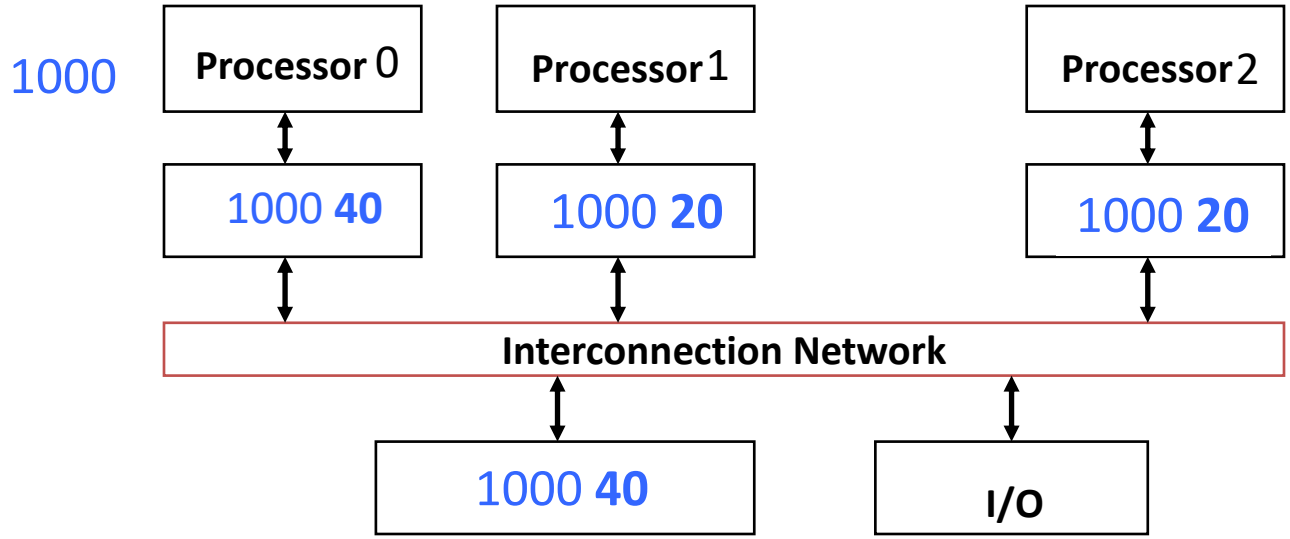
Shared Memory and Caches

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



Shared Memory and Caches

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



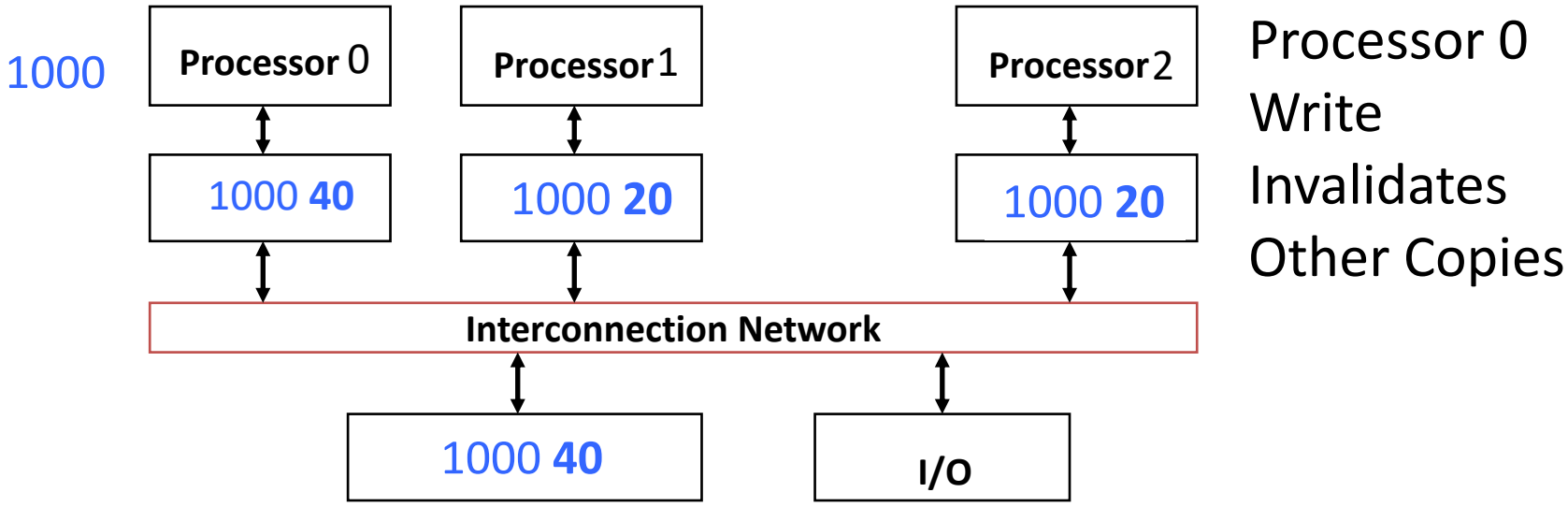
Problem?

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, other caches "snoop" the common interconnect checking for tags they hold
  - Invalidate any copies of same address modified in other cache

Shared Memory and Caches

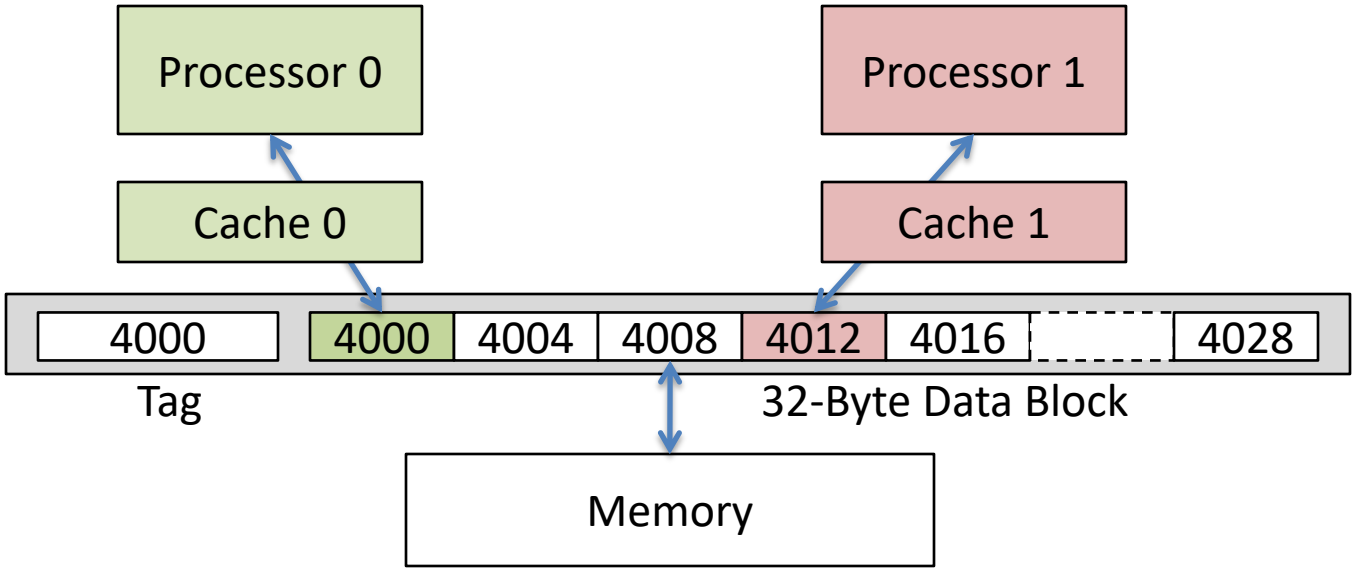
- Example, now with cache coherence
  - Processors 1 and 2 read Memory[1000]
  - Processor 0 writes Memory[1000] with 40



Question: Which statement(s) are 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**

Cache Coherency Tracked by Block



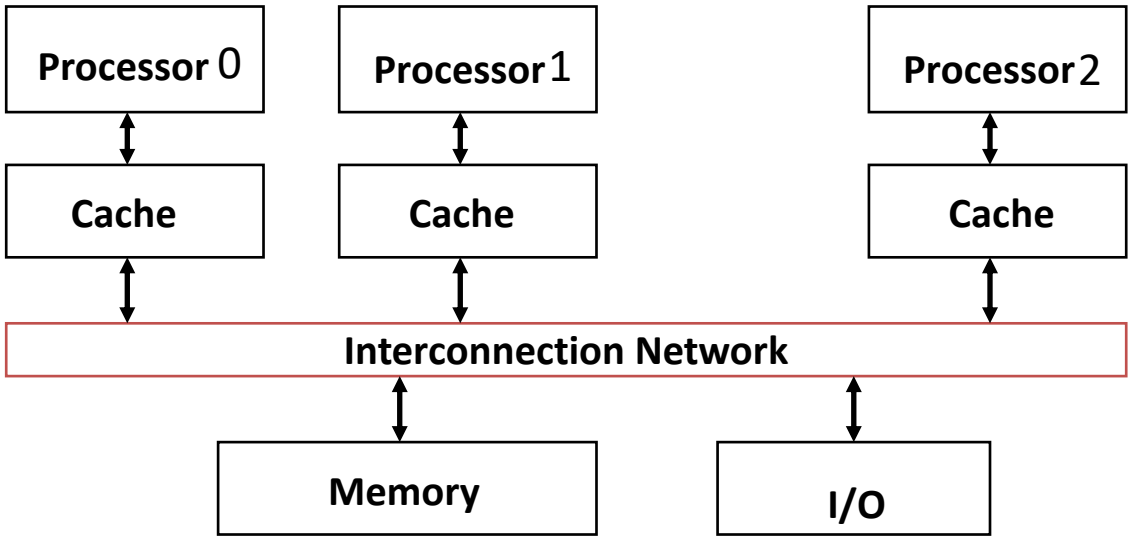
- Suppose block size is 32 bytes
- Suppose Processor 0 reading and writing variable X, Processor 1 reading and writing variable Y
- Suppose in X location 4000, Y in 4012
- What will happen?

Coherency Tracked by Cache Block

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

Shared Memory and Caches

- Use valid bit to ”unload” cache lines (in Processors 1 and 2)
- Dirty bit tells me: ”I am the only one using this cache line”! => no need to announce on Network!



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

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

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, reductions …
  - ≈ C: small so easy to learn, but not very high level and it's easy to get into trouble
  - Much we didn't cover – including other synchronization mechanisms (locks, etc.)