

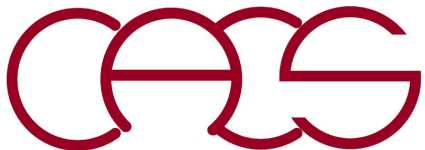
OpenMP Programming

Aiichiro Nakano

*Collaboratory for Advanced Computing & Simulations
Department of Computer Science
Department of Physics & Astronomy
Department of Quantitative & Computational Biology
University of Southern California*

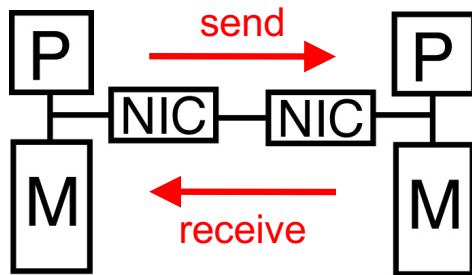
Email: anakano@usc.edu

Goal: Use multiple cores in a computing node *via* multithreading

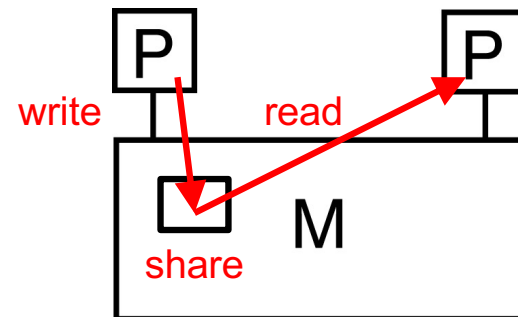


OpenMP

- Portable application program interface (API) for shared-memory parallel programming based on multi-threading by compiler directives
- OpenMP = Open specifications for Multi Processing
- OpenMP homepage
<https://www.openmp.org>
- OpenMP tutorial
<https://hpc-tutorials.llnl.gov/openmp>
- **Process:** an instance of program running
- **Thread:** a sequence of instructions being executed, possibly sharing resources with other threads within a process



MPI (distributed memory)

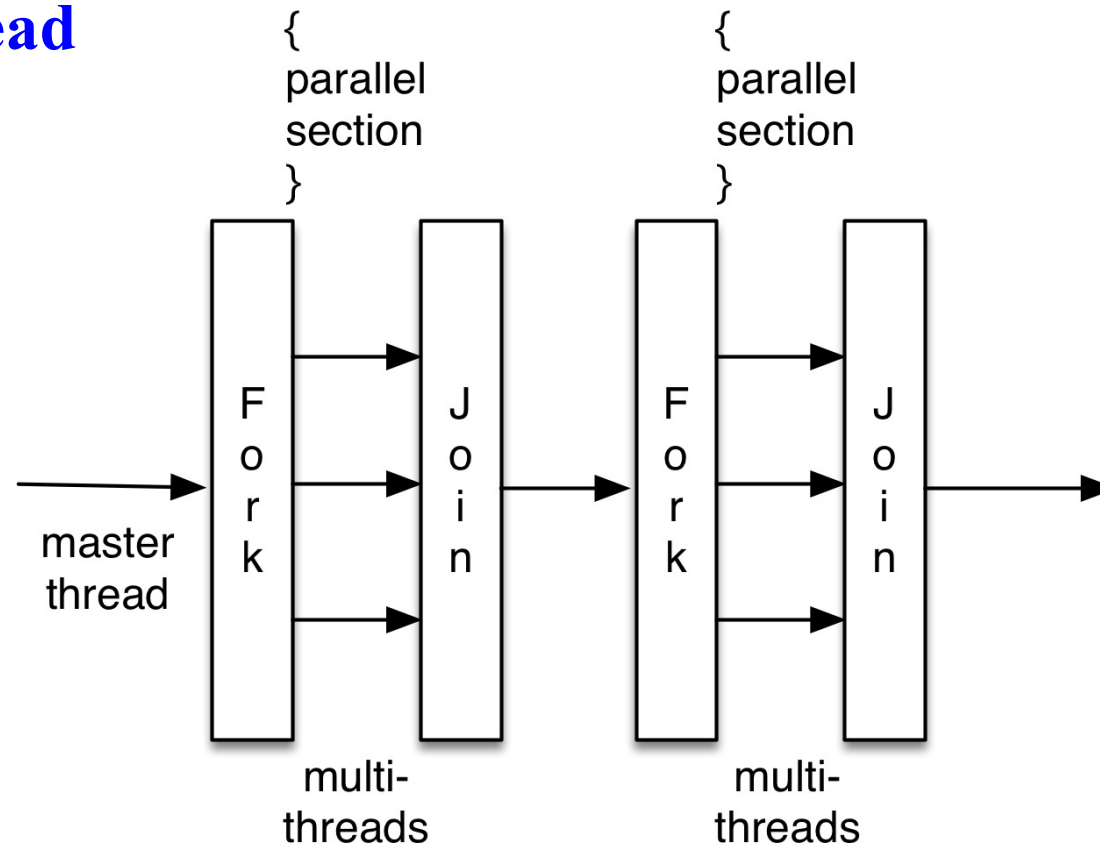


OpenMP (shared memory)

OpenMP Programming Model

Fork-join parallelism

- **Fork:** master thread spawns a team of threads as needed
- **Join:** when the team of threads complete the statements in the parallel section, they terminate synchronously, leaving only the master thread



- OpenMP threads communicate by sharing variables

OpenMP Example: `omp_example.c`

```
#include <stdio.h> https://aiichironakano.github.io/cs596/src/omp/omp\_example.c
#include <omp.h>
void main () {
    int nthreads,tid;
    nthreads = omp_get_num_threads(); ← Get the number of threads
    printf("Sequential section: # of threads = %d\n",nthreads);
    /* Fork multi-threads with own copies of variable */
    #pragma omp parallel private(tid)
    {
        /* Obtain & print thread id */
        tid = omp_get_thread_num(); ← Get my thread ID: 0, 1, ...
        printf("Parallel section: Hello world from thread %d\n",tid);
        /* Only master thread does this */
        if (tid == 0) {
            nthreads = omp_get_num_threads();
            printf("Parallel section: # of threads = %d\n",nthreads);}
    } /* All created threads terminate */
}
```

parallel section

- **Obtain the number of threads & my thread ID** (*cf.* `MPI_Comm_size` & `MPI_Comm_rank`)
- **By default, all variables are shared unless selectively changing storage attributes using private clauses**

OpenMP Example: omp_example.c

- **Compilation on `carc.usc.edu`**

gcc -o omp_example omp_example.c -fopenmp

- **Slurm script**

```
#!/bin/bash
```

```
#SBATCH --nodes=1
```

```
#SBATCH --ntasks-per-node=1
```

1 process per computing node

```
#SBATCH --cpus-per-task=2
```

2 cores (threads) per process

```
#SBATCH --time=00:00:59
```

```
#SBATCH --output=omp_example.out
```

```
#SBATCH -A anakano_429
```

```
export OMP_NUM_THREADS=2
```

Set the # of threads
using environment
parameter

```
./omp_example
```

- **Output**

```
Sequential section: # of threads = 1
```

```
Parallel section: Hello world from thread 1
```

```
Parallel section: Hello world from thread 0
```

```
Parallel section: # of threads = 2
```

Setting the Number of Threads

```
#include <stdio.h> https://aiichironakano.github.io/cs596/src/omp/omp\_example\_set.c
#include <omp.h>

void main () {
    int nthreads,tid;
    omp_set_num_threads(2);
    nthreads = omp_get_num_threads();
    printf("Sequential section: # of threads = %d\n",nthreads);
    /* Fork multi-threads with own copies of variable */
    #pragma omp parallel private(tid)
    {
        /* Obtain & print thread id */
        tid = omp_get_thread_num();
        printf("Parallel section: Hello world from thread %d\n",tid);
        /* Only master thread does this */
        if (tid == 0) {
            nthreads = omp_get_num_threads();
            printf("Parallel section: # of threads = %d\n",nthreads);
        }
    } /* All created threads terminate */
}
```

- **Setting the number of threads to be used in parallel sections within the program (no need to set OMP_NUM_THREADS); see `omp_example_set.c`**

OpenMP Programming Model

- OpenMP is typically used to parallelize (big) loops
- Use synchronization mechanisms to avoid race conditions (*i.e.*, the result changes for different thread schedules)
- **Critical section:** only one thread at a time can enter

```
#pragma omp parallel
{
    ...
    #pragma omp critical
    {
        ...
    }
    ...
}
```

Threads wait
their turn—
only one at a
time executes
the critical
section

Example: Calculating π

- Numerical integration

$$\int_0^1 \frac{4}{1+x^2} dx = \pi$$

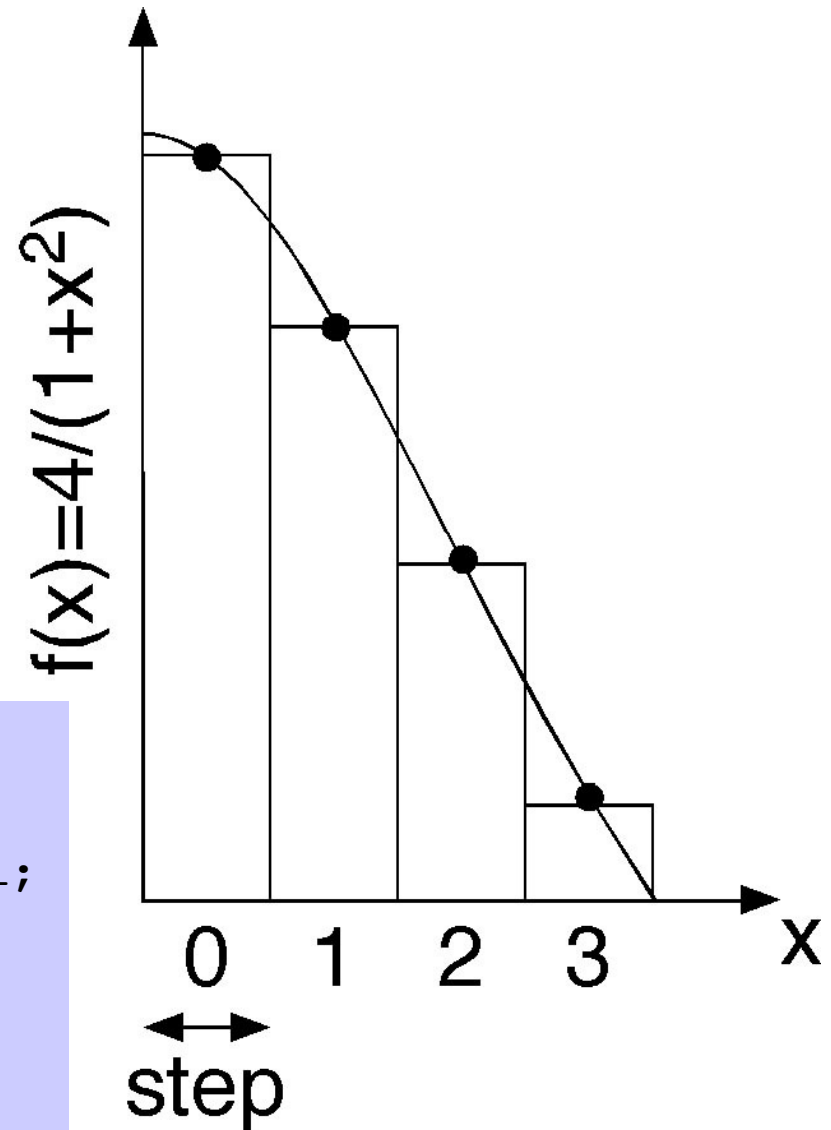
- Discretization:

$$\Delta = 1/N: \text{step} = 1/\text{NBIN}$$

$$x_i = (i+0.5)\Delta \quad (i = 0, \dots, N-1)$$

$$\sum_{i=0}^{N-1} \frac{4}{1+x_i^2} \Delta \cong \pi$$

```
#include <stdio.h>
#define NBIN 100000
void main() {
    long long i; double step,x,sum=0.0,pi;
    step = 1.0/NBIN;
    for (i=0; i<NBIN; i++) {
        x = (i+0.5)*step;
        sum += 4.0/(1.0+x*x);}
    pi = sum*step;
    printf("PI = %f\n",pi);
}
```



OpenMP Program: omp_pi_critical.c

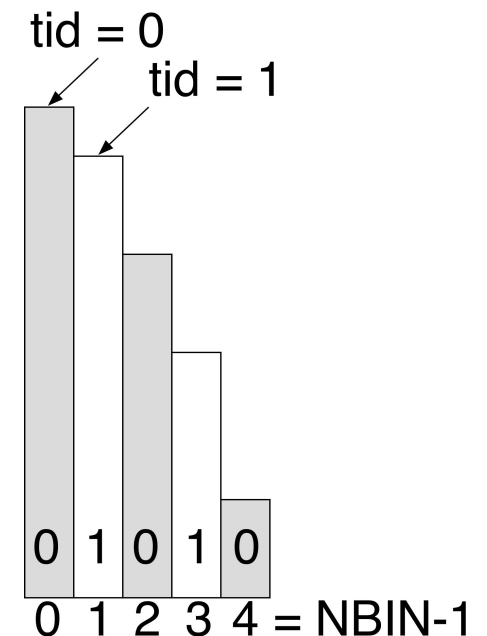
```
#include <stdio.h> https://aiichironakano.github.io/cs596/src/omp/omp\_pi\_critical.c
#include <omp.h>
#define NBIN 100000
void main() {
    double step, sum=0.0, pi;
    step = 1.0/NBIN;
    #pragma omp parallel
    {
        int nthreads, tid; long long i;
        double x;
        nthreads = omp_get_num_threads();
        tid = omp_get_thread_num();
        for (i=tid; i<NBIN; i+=nthreads) {
            x = (i+0.5)*step;
            #pragma omp critical
            sum += 4.0/(1.0+x*x);
        }
        pi = sum*step;
        printf("PI = %f\n", pi);
    }
}
```

Shared variables

Private (local) variables

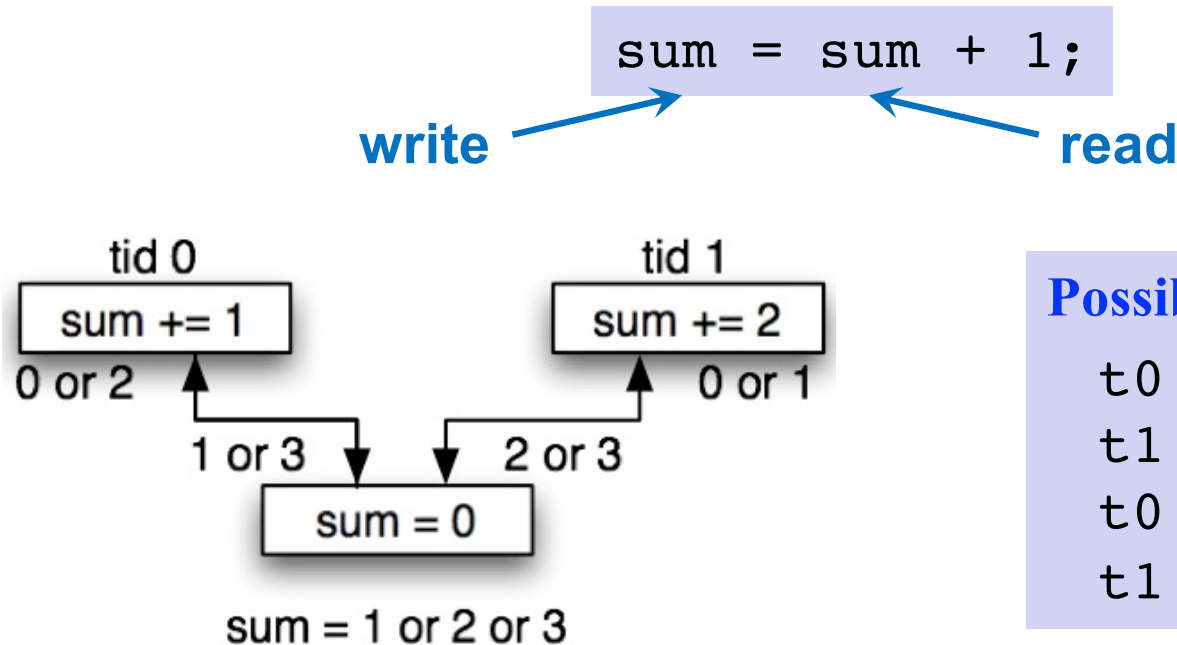
This has to be atomic

Thread-private variables: Either declare private or define within a parallel section



Race Condition

- **Race condition:** Output is dependent on the sequence or timing of how multiple threads are executed
- Race condition arises if the read & write operations below are not atomic (a set of operations is atomic if they are executed without being interrupted by other operations)



Possible scenarios

t0	r	0	t0	r	0
t1	r	0	t0	w	1
t0	w	1	t1	r	1
t1	w	2	t1	w	3

Critical Section

- Critical section degrades scalability, *cf.* Amdahl's law

$$T_P = fT_1 + (1-f)\frac{T_1}{P}$$
$$S_P = \frac{T_1}{T_P} = \frac{1}{f + \frac{1-f}{P}} \rightarrow \frac{1}{f} \quad (P \rightarrow \infty)$$

```
for (i=tid; i<NBIN; i+=nthreads) {  
    x = (i+0.5)*step;  
    #pragma omp critical  
    sum += 4.0/(1.0+x*x);  
}
```

$f \sim 0.5$

- How to get rid of the critical section?

Avoid Critical Section: omp_pi.c

Data privatization: Give each thread a dedicated accumulator

```
#include <stdio.h>
#include <omp.h>
#define NBIN 100000
#define MAX_THREADS 8
void main() {
    int nthreads,tid;
    double step,sum[MAX_THREADS]={0.0},pi=0.0;
    step = 1.0/NBIN;
    #pragma omp parallel private(tid)
    {
        long long i;
        double x;
        nthreads = omp_get_num_threads();
        tid = omp_get_thread_num();
        for (i=tid; i<NBIN; i+=nthreads) {
            x = (i+0.5)*step;
            sum[tid] += 4.0/(1.0+x*x);
        }
    }
    for(tid=0; tid<nthreads; tid++) pi += sum[tid]*step;
    printf("PI = %f\n",pi);
}
```

https://aiichironakano.github.io/cs596/src/omp/omp_pi.c

Array of partial sums for multi-threads

Private accumulator

Inter-thread reduction

Avoid Critical Section: “Wrong” Way

```
#include <stdio.h>
#include <omp.h>
#define NBIN 100000
void main() {
    double step,sum=0.0,pi;
    step = 1.0/NBIN;
    # pragma omp parallel
    {
        int nthreads,tid
        long long i;
        double x;
        nthreads = omp_get_num_threads();
        tid = omp_get_thread_num();
        for (i=tid; i<NBIN; i+=nthreads) {
            x = (i+0.5)*step;
            // #pragma omp critical
            sum += 4.0/(1.0+x*x);
        }
    }
    pi = sum*step;
    printf("PI = %f\n",pi);
}
```

omp_pi_noncritical.c

Everything You Learned About Parallel Computing is
Wrong for Machine Learning!

Prof. Kunle Olukotun (Stanford)
(Sep. 28, 2017 at USC)

**HOGWILD!: A Lock-Free Approach to Parallelizing
Stochastic Gradient Descent**

F. Niu *et al.*, [NeurIPS11](#)

```
[anakano@discovery src]$ ./omp_pi_critical
```

```
PI = 3.141593
```

```
[anakano@discovery src]$ ./omp_pi_noncritical
```

```
PI = 0.558481 ← 16-thread run
```

Load Balancing

- Interleaved assignment of loop-index values to threads balances the loads among the threads

```
for (i=tid; i<NBIN; i+=nthreads) {  
    ...  
}
```

A bad example




Most Widely Used Construct

- **OpenMP for:** Distribute the loop iterations across the threads; can be combined with OpenMP parallel to achieve multithreading in just one line.

```
#include <omp.h>
#include <stdio.h>
#define NBIN 100000
void main() {
    long long i;
    double step,x,sum=0.0,pi;
    step = 1.0/NBIN;
    omp_set_num_threads(2);
    # pragma omp parallel for private (i,x) reduction(+:sum)
    for (i=0; i<NBIN; i++) {
        x = (i+0.5)*step;
        sum += 4.0/(1.0+x*x);
    }
    pi = sum*step;
    printf("PI = %f\n",pi);
}
```

Reduction clause performs automatic thread reduction



- OpenMP parallelization is very easy!

Where to Go from Here

- **OpenMP tutorial introducing most constructs**
<https://hpc.llnl.gov/tuts/openMP>
- **OpenMP 4.5 has added many constructs to support modern hardware architectures**

#pragma omp target: Offload computation to accelerators like graphics processing units (GPUs)

#pragma omp simd: Explicit control over single instruction multiple data (or vector) operations

<https://www.openmp.org/wp-content/uploads/openmp-4.5.pdf>

