OpenMP Programming

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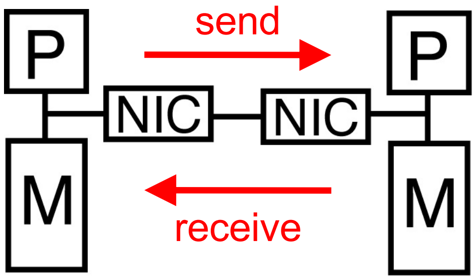
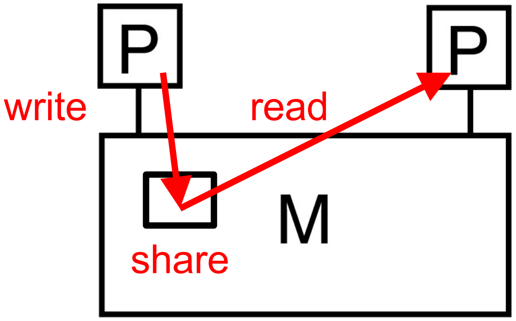
Goal: Use multiple cores in a computing node *via* multithreading

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)

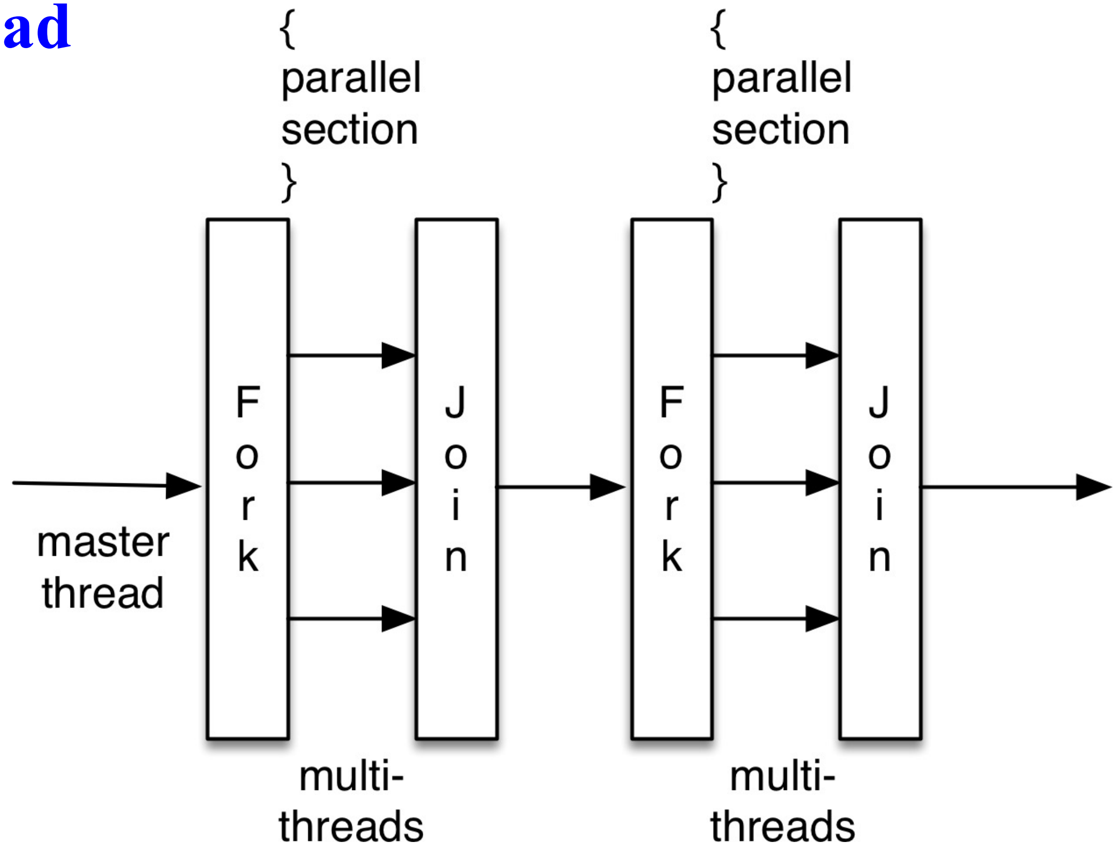


OpenMP (shared memory)

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

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

```c
#include <stdio.h>
#include <omp.h>
void main () {
  int nthreads,tid;
  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 */
}
```

Get the number of threads

Each threads gets a private variable

Get my thread ID: 0, 1, ...

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
./omp_example
```

Set the # of threads using environment parameter

- **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**

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

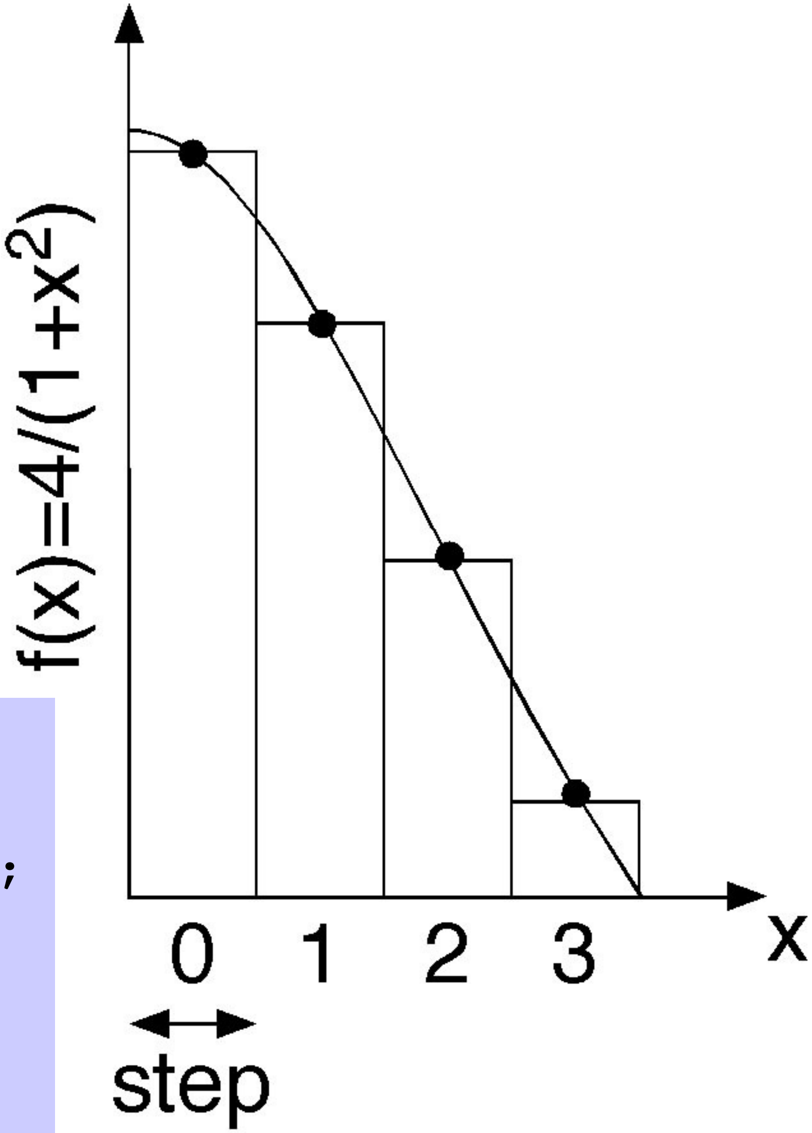
- **Discretization:**

$\Delta = 1/N$: `step = 1/NBIN`

$x_i = (i+0.5)\Delta \; (i = 0,\ldots,N\text{-}1)$

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

```
#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

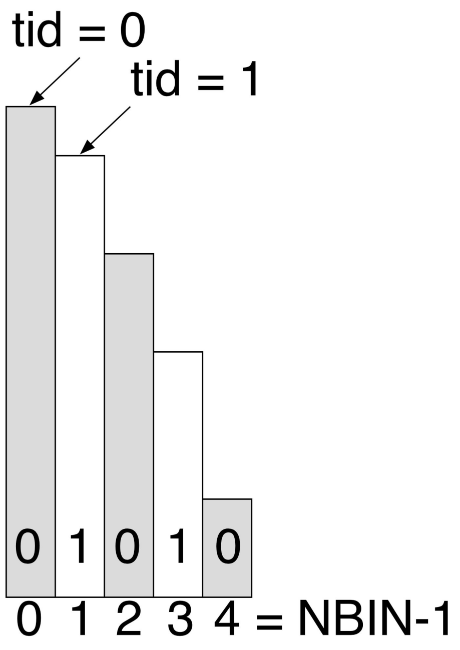
https://aiichironakano.github.io/cs596/src/omp/omp_pi_critical.c

```
#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);
}
```

Shared variables

Private (local) variables

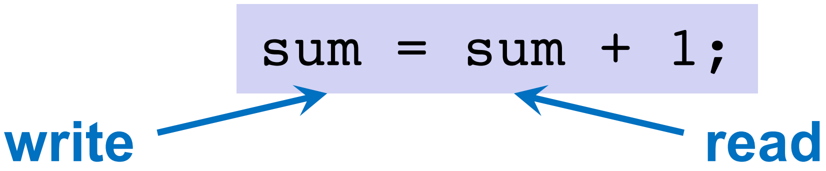
This has to be atomic



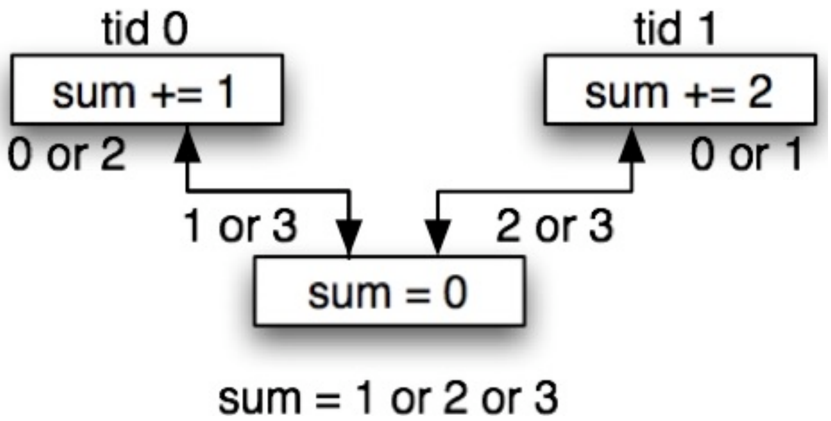
Thread-private variables: Either declare private or define within a parallel section

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)**



```
sum = sum + 1;
```



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

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

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

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

$f \sim \mathbf{0.5}$

- How to get rid of the critical section?

Avoid Critical Section: omp_pi.c

Data privatization: Give each thread a dedicated accumulator

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

```
#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);
}
```

Array of partial sums for multi-threads

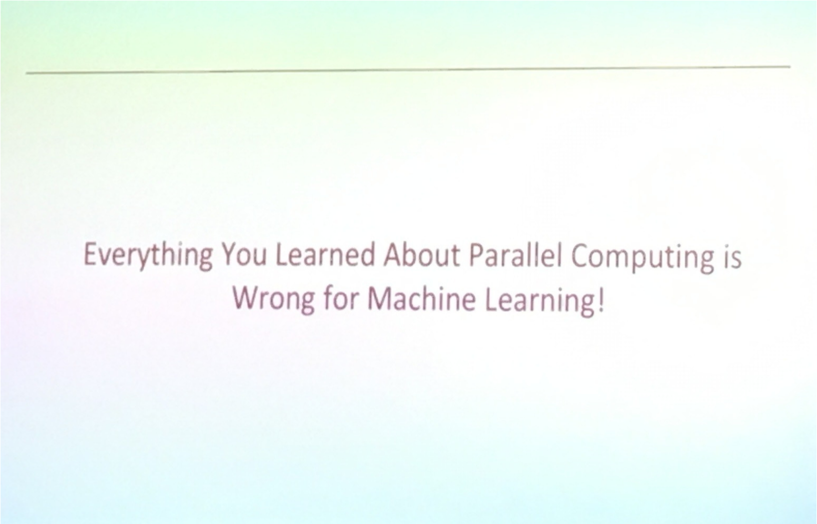
Private accumulator

Inter-thread reduction

Avoid Critical Section: “Wrong” Way

omp_pi_noncritical.c

```
#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);
}
```



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

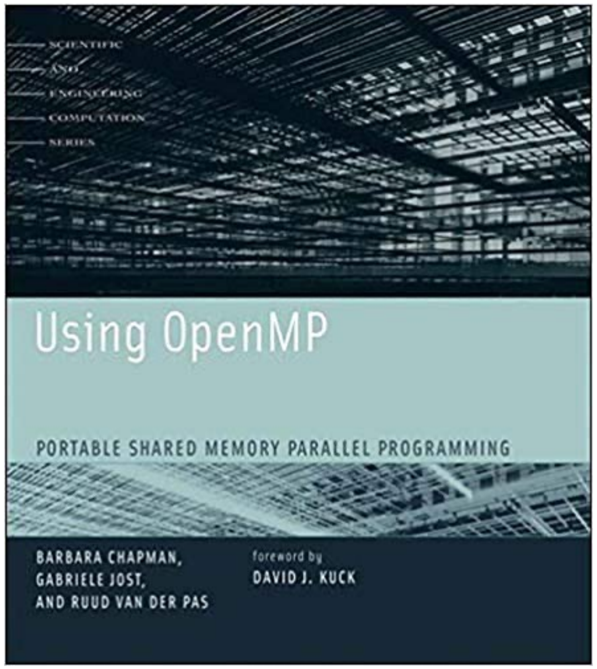
- **OpenMP tutorial introducing most constructs**
  https://hpc-tutorials.llnl.gov/openmp

- **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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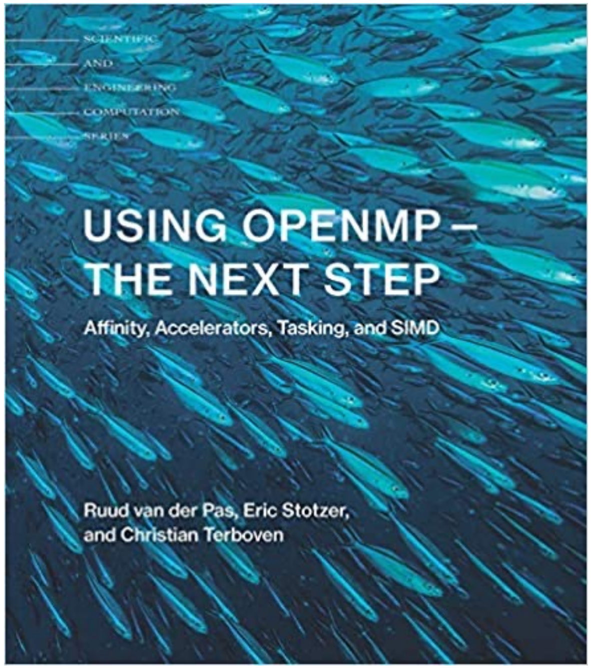
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