Programming Shared-Memory Parallel Systems - OpenMP

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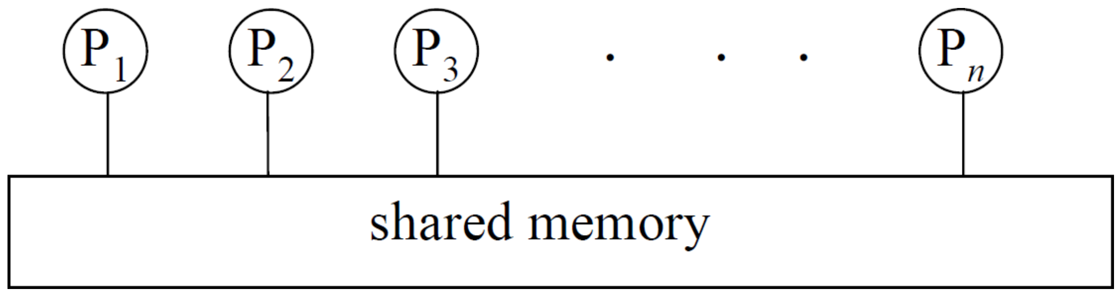
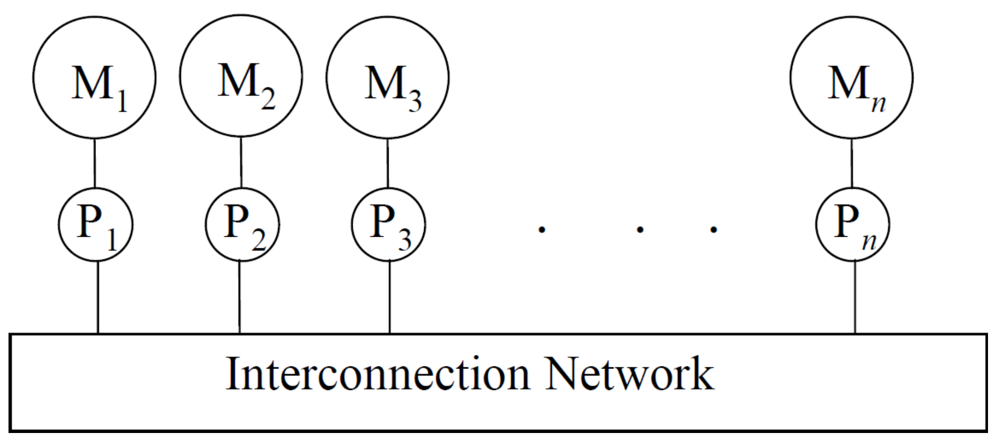
Parallel and Distributed Computing

- The **difference** **includes** whether the **processes** **communicate** using **shared** or a **distributed memory**





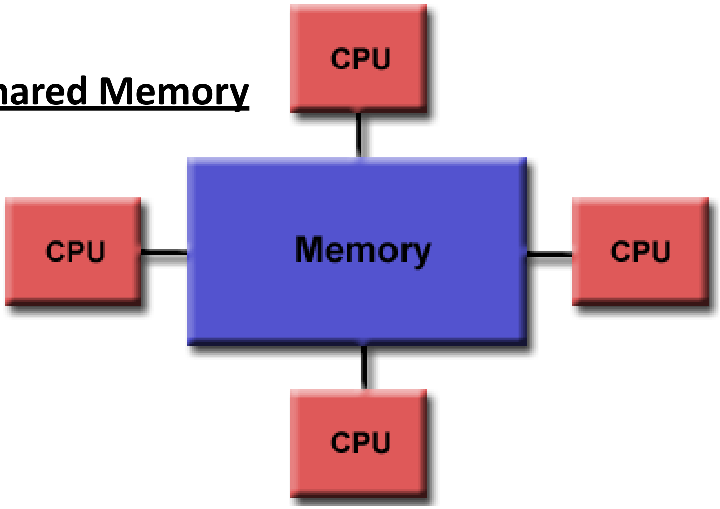
OpenMP

- **Programming** of **shared memory systems**
- An **API** for **Fortran** and **C/C++**
  - **Directives**
  - **Runtime routines**
  - **Environment variables**

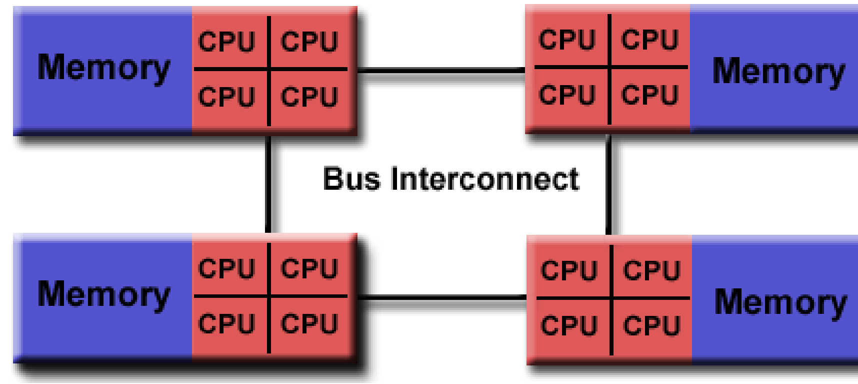
Lecture credits: https://computing.llnl.gov/tutorials/openMP/

Memory Models

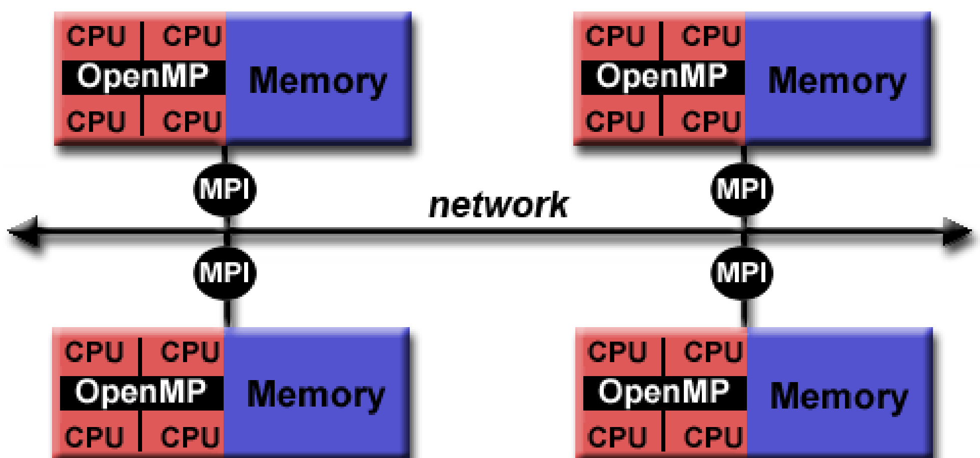
Shared Memory



Distributed Memory



Hybrid Memory



Goals

- **Standardization**
  - **Provide** a **standard** among a **variety of shared memory architectures** (platforms)
- **High-level interfaces** to **thread programming**
- **Multi-vendor support**
- **Multi-OS support** (Unix, Windows, Mac, etc.)
- The **MP** in **OpenMP** is for **M**ulti-**P**rocessing
- *Don't confuse **OpenMP** with **Open MPI**! :)*

Credits: http://its.unc.edu/research-computing.html

Release History

Date	Version
Oct 1997	Fortran 1.0
Oct 1998	C/C++ 1.0
Nov 1999	Fortran 1.1
Nov 2000	Fortran 2.0
Mar 2002	C/C++ 2.0
May 2005	OpenMP 2.5
May 2008	OpenMP 3.0
Jul 2011	OpenMP 3.1
Jul 2013	OpenMP 4.0
Nov 2015	OpenMP 4.5
Nov 2018	OpenMP 5.0

Programming Shared Memory Systems

- **Explicit Parallelism**
  - For example, **pthreads**

- **Programmer Directed**
  - For example, **OpenMP**

Hello World – pthreads based version

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

void* thrfunc(void* arg) {
        printf("hello from thread %d\n", *(int*)arg);
}

int main(void) {
        pthread_t thread[4];
        pthread_attr_t attr;
        int arg[4] = {0,1,2,3};
        int i;
        // setup joinable threads
        pthread_attr_init(&attr);
        pthread_attr_setdetachstate(&attr,PTHREAD_CREATE_JOINABLE);
        // create N threads
        for(i=0; i<4; i++)
                pthread_create(&thread[i], &attr, thrfunc, (void*)&arg[i]);


        // wait for the N threads to finish
        for(i=0; i<4; i++)
                pthread_join(thread[i], NULL);
}
```

... and the OpenMP version

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

int main(int argc, char* argv[])
{
   #pragma omp parallel  {
   printf("Hello World... from thread = %d\n", omp_get_thread_num());
   }
}
```

Compilation: $ **gcc -fopenmp hello.c -o hello**

Execution: $ **export OMP_NUM_THREADS=4**

$ **./hello**

Demo: hello.c

Compiling

Intel (**icc**, **ifort**, **icpc**)

`-openmp`

PGI (**pgcc**, **pgf90**, …)

`-mp`

GNU (**gcc**, **gfortran**, **g++**)

`-fopenmp`

OpenMP - User Interface Model

- **Shared Memory** with **thread based parallelism**
- **Not a new language**
- **Compiler directives, library calls,** and **environment variables extend the base language**
  - f77, f90, f95, C, C++
- **Not automatic parallelization**
  - User **explicitly specifies parallelism**
  - **NOTE: Compiler does not ignore** user **directives even if wrong**

OpenMP - Syntax

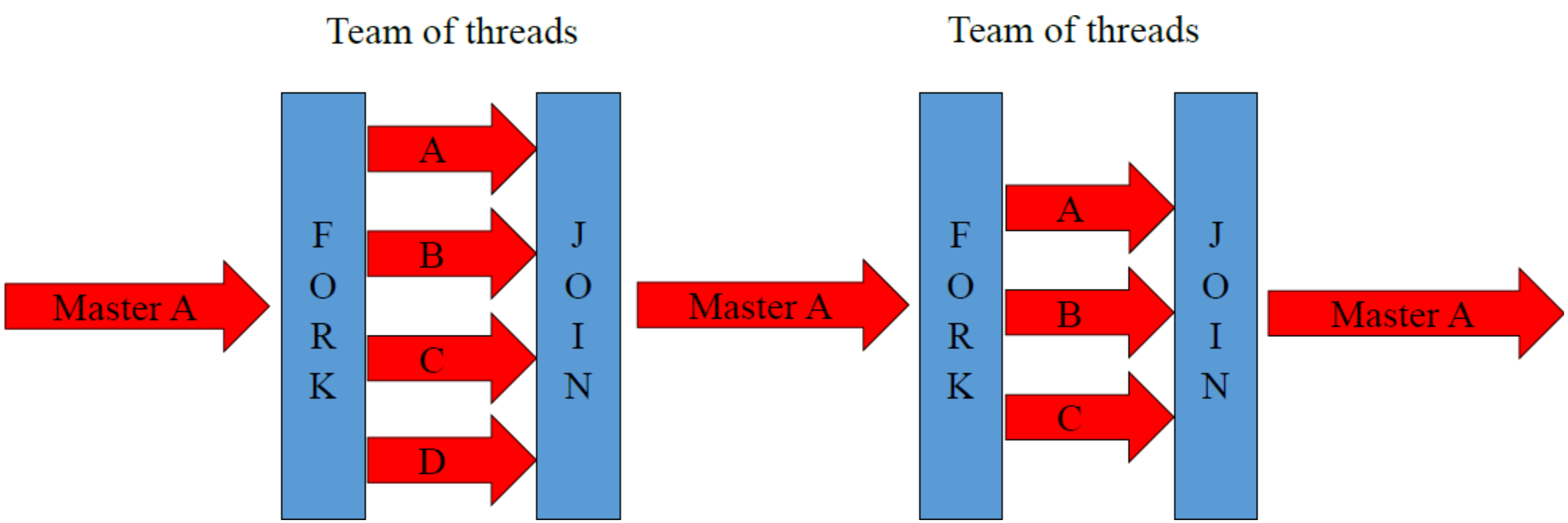
- **Parallelism** is **highlighted** using **compiler directives** or **pragmas**

- **For C and C++,** the **pragmas take the form**:
  `#pragma omp construct [clause [clause]…]`

- **Any compiler** (even if it **does not have OpenMP** support) **can compile** the **program** (with **no parallelism though**)

Fork*/Join Execution Model

- An **OpenMP program starts** as a **single thread** (***master thread***).
- **Additional threads** (*Team*) are **created** when the <u>master hits a parallel region</u>.
- When **<u>all threads finished the parallel region</u>**, the **new threads** are **given back** to the **runtime** or operating system



***Not to be confused with fork() system call**

Using OpenMP

- **OpenMP** is **usually used** to parallelize loops:
  - **Find most time consuming loops**
  - **Split them** among **threads**

Split-up this loop between multiple threads

```
void main( )
{
    double Res[1000];

    for(int i=0;i<1000;i++) {
        do_huge_comp(Res[i]);
    }
}
```

Sequential program

```
void main( )
{
    double Res[1000];
    #pragma omp parallel for
    for(int i=0;i<1000;i++) {
        do_huge_comp(Res[i]);
    }
}
```

Parallel program

OpenMP Directives

OpenMP - Directives

- **OpenMP compiler directives** are **used** for **various purposes**:
  - **Spawning** a **parallel region**
  - **Dividing blocks** of **code** among threads
  - **Distributing loop iterations** between threads
  - …

sentinel directive-name [clause, ...]

#pragma omp parallel private(var)

Supported Clauses for the Parallel Construct

Valid Clauses:

if (logical expression)

num_threads (integer)

private (list of variables)

firstprivate (list of variables)

shared (list of variables)

default (none|shared|private **fortran only**)

copyin (list of variables)

reduction (operator: list)

...

OpenMP Constructs

- **OpenMP constructs** can be divided into **5 categories:**
  1. **Parallel Regions**
  2. **Work-sharing**
  3. **Data Environment**
  4. **Synchronization**
  5. **Runtime functions/environment variables**

OpenMP: Parallel Regions

- You create **threads** in **OpenMP** with "**omp parallel**" pragma
- For example: a **4-thread based Parallel region**:

```
int A[10];
omp_set_num_threads(4);
#pragma omp parallel
{
    int ID =omp_get_thread_num();
    fun1(ID,A);
}
```

Demo: helloFun.c

- **Implicit barrier at the end of parallel block**
- **Each thread calls fun1(ID,A)** ***for ID = 0 to 3***
- **Each thread executes** the **<u>same code</u>** within the block

Credits: University of Houston

The *parallel* directive

- A **parallel region** is a **block** of **code** that will **be executed by multiple threads**
- **When** (in **serial program**) a **PARALLEL directive** is **found**, a **team of threads** is **created** and **main-thread** (serial execution thread) **becomes** the **master of the team**
- **Master thread** has **id** or **number** **0** (***within that team***)
- **The code is duplicated** and **all threads will execute that code**
- There is an **implicit barrier** at the **end of a parallel region**
- **Master** **thread** **continues execution** after this point

The *parallel* directive

- Some common clauses include:
  - **if** *(expression)*
  - **private** *(list)*
  - **shared** *(list)*
  - **num_threads** *(integer-expression)*

How Many Threads?

- The **number of threads** in a **parallel region** is **determined** by the **following factors**, ***<u>in order of precedence</u>***:
  1. **Evaluation** of the **if** clause
  2. **Setting** of the **NUM_THREADS** clause
  3. Use of the **omp_set_num_threads( )** library function
  4. Setting of the **OMP_NUM_THREADS** **environment variable**
  5. **Implementation default:** Usually the ***number of CPUs on a node***

- **Threads** are **numbered** from **0** (master thread) to **N-1**

IF clause

```
#pragma omp parallel if (scalar_expression)
```

- **Execute** in **parallel** **if expression is true**
  - **Otherwise serial execution**

NUM_THREADS clause

```
#pragma omp parallel if(np>1) num_threads(np)
{
    …
}
```

- **Execute** in **parallel** **if expression is true**
- **Executes using *np* number of threads**

omp_set_num_threads( ) function

```
#define TOTAL_THREADS 8
int main( )
{
    omp_set_num_threads(TOTAL_THREADS);
    #pragma omp parallel
    {
        . . .
    }
. . .
```

- **Execute** in **parallel** **using 8 threads**

OMP_NUM_THREADS – Environment Variable

```
$ export OMP_NUM_THREADS=4
$ echo $OMP_NUM_THREADS
```

- **Sets** and **displays** the **value** of the **environment variable** **OMP_NUM_THREADS**

Execution Status in Parallel Region

```
int omp_in_parallel()
```

- **Returns non-zero: if execution is in parallel region**
- **Returns zero: if execution in non-parallel region**

Demo: PRegion.c

Shared and Private Data

- **Shared data** are **accessible** by **all threads**
- A **reference** **`a[5]`** to a **shared array** **accesses** the **same address in all threads**
- **Private data** are **accessible only** by **a thread**
  - **Each thread** has its **own copy**
- The **default** is **shared**

Shared and Private Data

```c
int main(int argc, char* argv[])
{
    int threadData = 10;

    // Beginning of parallel region
    #pragma omp parallel private(threadData)
    {
        threadData =200;
    }

    // Ending of parallel region
    printf("Value: %d\n", threadData);
}
```

Demo: SPData.c

Shared and Private Data

```
#pragma omp parallel shared(list)
```

- Default behavior
- List will be shared
- Each thread access the same memory location
- Initial value (for the first thread) will be same as before the region
- Final value will be updated by the last thread leaving the region
- Problems: Data Race

Shared and Private Data

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

- **Data local to thread**
- You **should not rely** on any **initial and terminal value (after execution of the parallel region)**
- **Separate "Stack Memory" for each thread's private data**
- **No storage associated** with **original object (even with same name for data-items)**

- Use ***firstprivate*** and/or ***lastprivate clause*** to override

Shared and Private Data

```
#pragma omp parallel firstprivate (list)
```

- **Variables** in **list** are **private**
- **Initialized** with the **value** the **variable had** ***before*** **entering** the **construct**

```
#pragma omp parallel for lastprivate (list)
```

- **Used in "for" loops**
- **Variables** in **list** are **private**
- The **thread** that **executes** the ***final iteration of the loop*** **updates** the **value** (of the variables in the list)

Shared and Private Data

- Alter the default behavior
- To implement customized access behavior

Shared and Private Data – Example (1/4)

```
#include <omp.h>
#include <stdio.h>
int main() {
  int i;
  const int N = 1000;
  int a = 50;
  int b = 0;

#pragma omp parallel for default(shared)
  for (i=0; i<N; i++) {
    b = a + i;
  }

  printf("a=%d b=%d (expected a=50 b=1049)\n", a, b);
}
```

Demo: SPDE1.c

Shared and Private Data – Example (2/4)

```
#include <omp.h>
#include <stdio.h>
int main() {
  int i;
  const int N = 1000;
  int a = 50;
  int b = 0;

#pragma omp parallel for default(none) private(i) private(a) private(b)
  for (i=0; i<N; i++) {
    b = a + i;
  }

  printf("a=%d b=%d (expected a=50 b=1049)\n", a, b);
}
```

Demo: SPDE1.c

Shared and Private Data – Example (3/4)

```
#include <omp.h>
#include <stdio.h>
int main() {
  int i;
  const int N = 1000;
  int a = 50;
  int b = 0;

#pragma omp parallel for default(none) private(i) private(a) lastprivate(b)
  for (i=0; i<N; i++) {
    b = a + i;
  }

  printf("a=%d b=%d (expected a=50 b=1049)\n", a, b);
}
```

Demo: SPDE1.c

Shared and Private Data – Example (4/4)

```c
#include <omp.h>
#include <stdio.h>
int main() {
  int i;
  const int N = 1000;
  int a = 50;
  int b = 0;

#pragma omp parallel for default(none) private(i) firstprivate(a) lastprivate(b)
  for (i=0; i<N; i++) {
    b = a + i;
  }

  printf("a=%d b=%d (expected a=50 b=1049)\n", a, b);
}
```

Demo: SPDE1.c

Getting ID of Current Thread

```c
int main(int argc, char* argv[])
{
  int iam, nthreads;
  #pragma omp parallel private(iam,nthreads) num_threads(2)
  {
      iam = omp_get_thread_num();
      nthreads = omp_get_num_threads();
      printf("ThradID %d, out of %d threads\n", iam, nthreads);
      if (iam == 0)
          printf("Here is the Master Thread.\n");
      else
          printf("Here is another thread.\n");
   }

}
```

Demo: CTID.c

Work-Sharing Constructs

- If **all** the **threads** are **doing** the **same thing**, ***what is the advantage then?***

- **Within** each "**Team**" **threads are assigned IDs**, with **master thread** assigned **ID 0**
  - `omp_get_thread_num()` `//to get thread number`

Can we use this to distribute tasks amongst the "team" members?

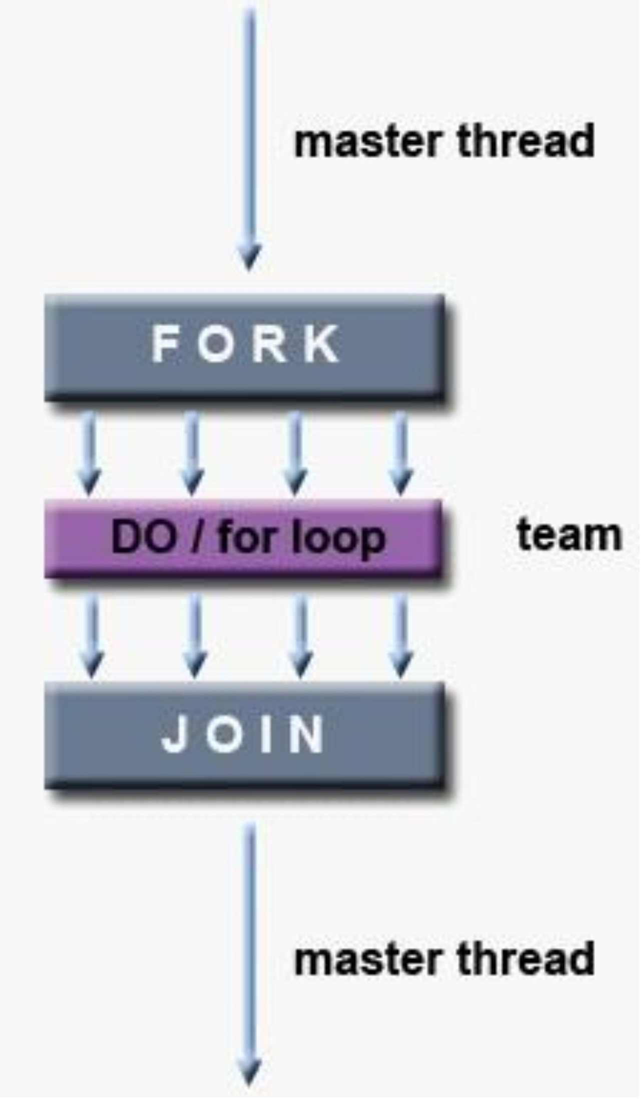
- **Work-sharing constructs distribute** the **specified work** to **all threads** within the **current team**

- **Work-sharing constructs do not launch new threads**

For Work-Sharing Construct

- **for** - **shares iterations** of a **loop across the team**

#pragma omp for [clause ...] newline



There is an implicit synchronization after ***#pragma omp for***

For Work-Sharing Construct

- **SCHEDULE clause describes how iterations** of the **loop** are **divided among the threads** in the team

STATIC

Chunks of specified size assigned round-robin

DYNAMIC

Chunks of specified size are assigned when thread finishes previous chunk (*work-Stealing mechanism*)

Do/For Work-Sharing Construct

```
int main(int argc, char* argv[])
{
        int i, a[10];
        #pragma omp parallel num_threads(2)
        {
                #pragma omp for schedule(static, 2)
                for ( i=0; i<10;i++)
                        a[i] = omp_get_thread_num();
        }

        for ( i=0; i<10;i++)
                printf("%d",a[i]);
}
```

Demo: ForConst.c

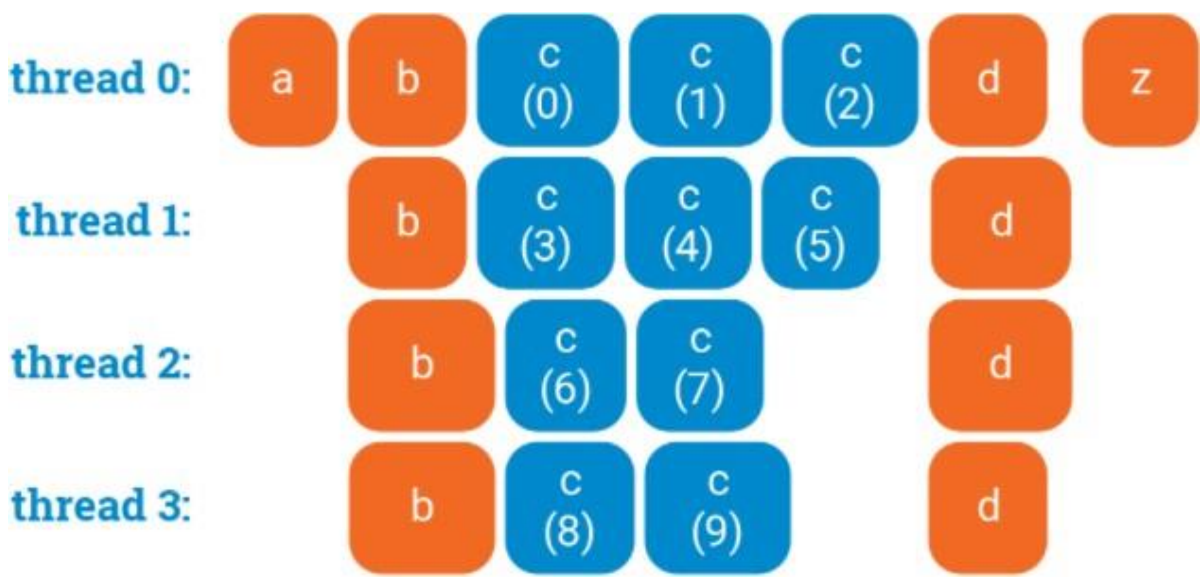
Do/For Work-Sharing Construct

```c
int main(int argc, char* argv[])
{
    int sum, counter, inputList[6] = {11,45,3,5,12,-3};
    #pragma omp parallel num_threads(2)
    {
       #pragma omp for schedule(static, 3)
      for (counter=0; counter<6; counter++) {
           printf("%d adding %d to the
           sum\n",omp_get_thread_num(), inputList[counter]);

           sum+=inputList[counter];
       } //end of for
    } //end of parallel section

    printf("The summed up Value: %d", sum);
}
```

Demo: ForConst2.c

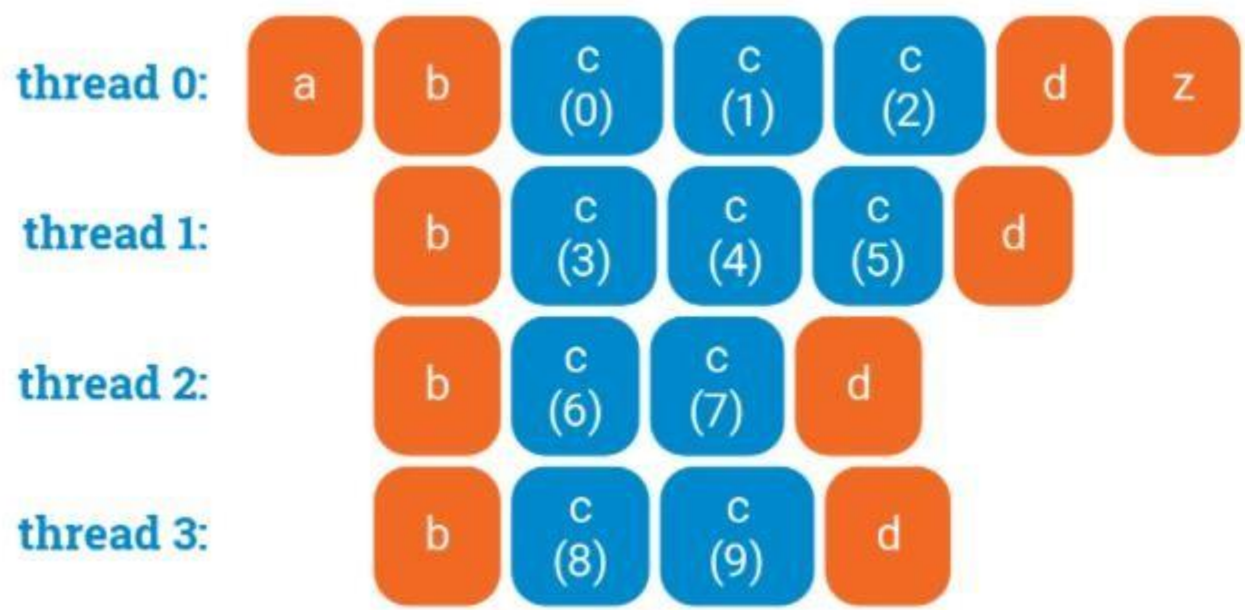
For Work-Sharing –Synchronized

```
a();
#pragma omp parallel
{
    b();
    #pragma omp for
    for (int i = 0; i < 10; ++i) {
        c(i);
    }
    d();
}
z();
```



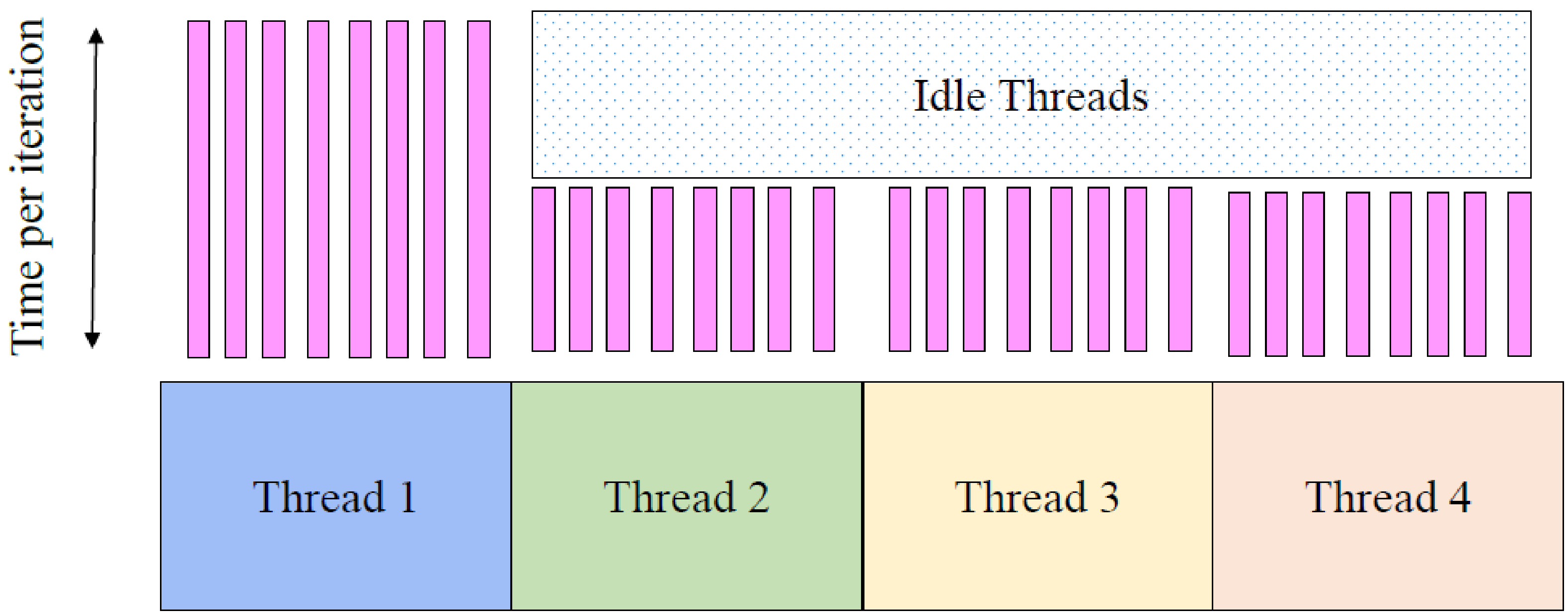
For Work-Sharing – Non Synchronized

```
a();
#pragma omp parallel
{
    b();
    #pragma omp for nowait
    for (int i = 0; i < 10; ++i) {
        c(i);
    }
    d();
}
z();
```



Problems with Static Scheduling

- **What happens if** loop **iterations do not take** the **same** amount of **time**?
  - **Load imbalance**



Dynamic Scheduling

- **Fixed size** chunks **assigned on the fly**
  - Work-stealing mechanism

- **Disadvantage:** more overhead as compared to Static

```
#pragma omp parallel for default(shared) private(j) schedule(dynamic,10)
  for (j=0; j<N; j++) {
        ... // some work here
}
```

1	2	3	4	2	3	4	3	4	1	1	2	3	4	3

Demo: LoopSched.c

Threads share Global variables!

```
#include <pthread.h>
#include <iostream>
#include <unistd.h>
using namespace std;
#define NUM_THREADS 10

int sharedData = 0;
void* incrementData(void* arg) {
     sharedData++;
     pthread_exit(NULL);
}

int main()
{
    pthread_t threadID;
    for (int counter=0; counter<NUM_THREADS;counter++) {
         pthread_create(&threadID, NULL, incrementData, NULL);
    }
    cout << "ThreadCount:" << sharedData <<endl;
    pthread_exit(NULL);
}
```

The output for the pthread version?

```
>./globalData
ThreadCount:10

>./globalData
ThreadCount:8
```

ThreadCount: A better implementation

```
#include <pthread.h>
#include <iostream>
#include <unistd.h>
using namespace std;
#define NUM_THREADS 100
int sharedData = 0;
void* incrementData(void* arg)
{
    sharedData++;
    pthread_exit(NULL); }

int main()
{
   pthread_t threadID[NUM_THREADS];
   for (int counter=0; counter<NUM_THREADS;counter++) {
      pthread_create(&threadID[counter], NULL, incrementData, NULL);
   }
   //waiting for all threads
   int statusReturned;
   for (int counter=0; counter<NUM_THREADS;counter++) {
      pthread_join(threadID[counter], NULL);
    }
   cout << "ThreadCount:" << sharedData <<endl;
   pthread_exit(NULL);
}
```

Is the problem solved?

- **Unfortunately, not yet :(**
- The **output** from **running it with 1000 threads** is as below:

```
>./6join
ThreadCount:990
>./6join
ThreadCount:978
>./6join
ThreadCount:1000
>
```

- **Reasons?**
- **What can be done?**

ThreadCount: OpenMP Implementation

```
int main(int argc, char* argv[])
{
  int threadCount=0;
  #pragma omp parallel num_threads(100)
  {
     int myLocalCount = threadCount;
     sleep(1);
     myLocalCount++;
     threadCount = myLocalCount;


  }
  printf("Total Number of Threads: %d\n", threadCount);
}
```

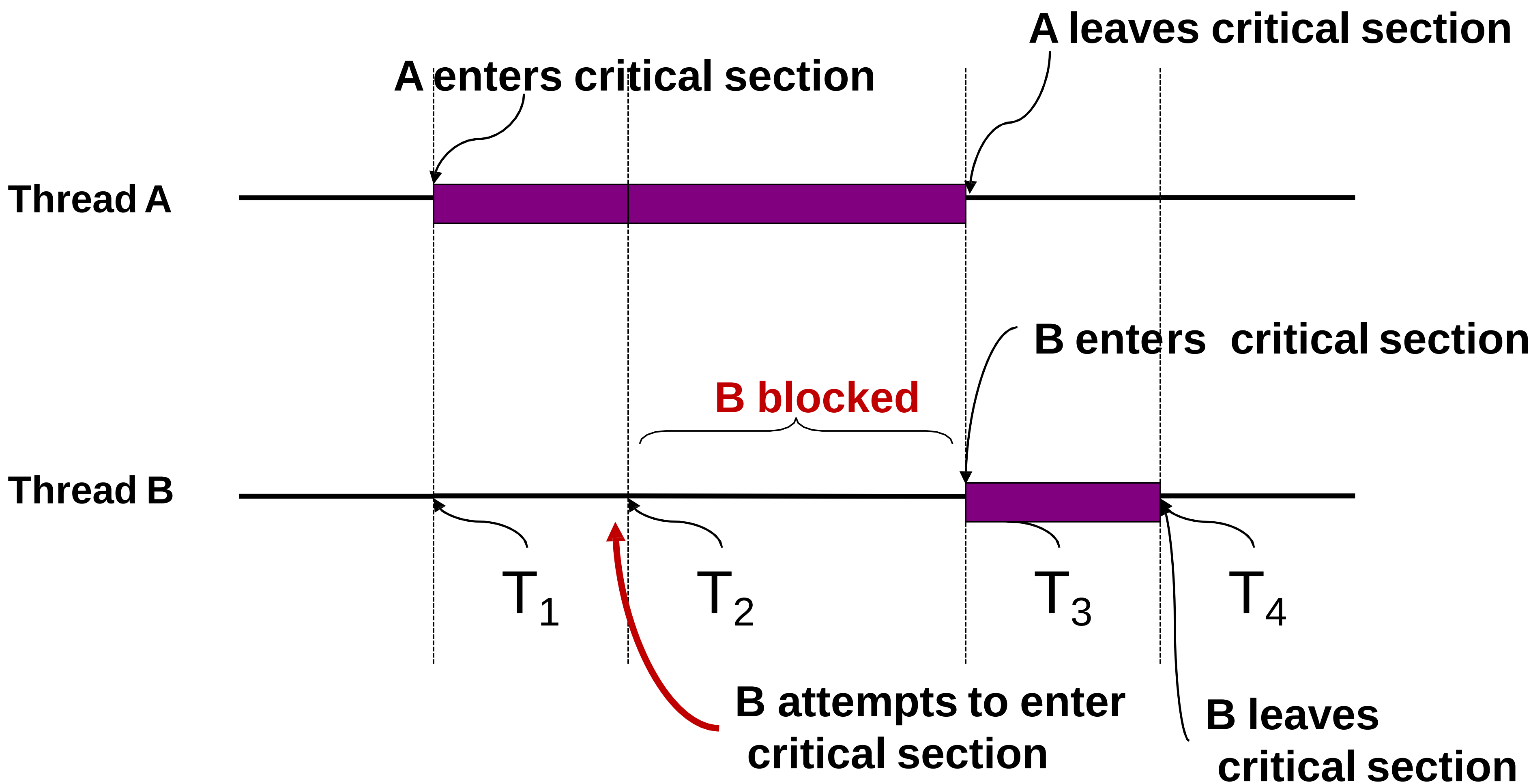
Demo: TCount1.c

Critical-Section (CS) Problem

- ***n*** **processes** all **competing** to **use** some **shared data**
- **Each process** has a **code segment**, called **critical section**, in which the **shared data is accessed**

- **Problem (ensures that):**
  –**Two process** are **not allowed** to **execute** in their **critical section at the same time**
  – **Access** to the **critical section** must be an **atomic action**

Critical Section



Mutual Exclusion

At any given time, only one Thread is in the critical section

...back to threads counting

```
int sharedData = 0;
pthread_mutex_t mutexIncrement;

void* incrementData(void* arg)
{
    pthread_mutex_lock(&mutexIncrement);
    sharedData++;
    pthread_mutex_unlock(&mutexIncrement);
    pthread_exit(NULL);
}

int main()
{
  pthread_mutex_init(&mutexIncrement, NULL);


  pthread_t threadID[NUM_THREADS];
   for (int counter=0; counter<NUM_THREADS;counter++) {
      pthread_create(&threadID[counter], NULL, incrementData,
      NULL);
   }
   //waiting for all threads
   int statusReturned;
   for (int counter=0; counter<NUM_THREADS;counter++)
      { pthread_join(threadID[counter], NULL);
    }
   cout << "ThreadCount:" << sharedData
   <<endl; pthread_exit(NULL);
}
```

OpenMP - Synchronization Constructs

- The **CRITICAL** **directive** **specifies** a **region of code** that **must** be **executed** by **only one thread at a time**

- If a **thread** is **currently executing** inside a **CRITICAL region** and **another thread attempts** to **execute it**, **it will block until the first thread exits** that CRITICAL region.

```
pragma omp critical [ name ]
...
```

… back to threadCount

```
int main(int argc, char* argv[])
{
   int threadCount;
   #pragma omp parallel num_threads(5)
   {
      #pragma omp critical
      {
          int myLocalCount = threadCount;
          sleep(1);
          myLocalCount++;
          threadCount = myLocalCount;
      }
   }
   printf("Total Number of Threads: %d\n", threadCount);
}
```

Demo: TCount2.c

OpenMP - Synchronization Constructs

- The **MASTER directive specifies** a **region** that is to be **executed only by the master thread** of the **team**

- **All other threads** on the team **skip this section** of **code**

```
#pragma omp master
...
```

Demo: MasterOnly.c

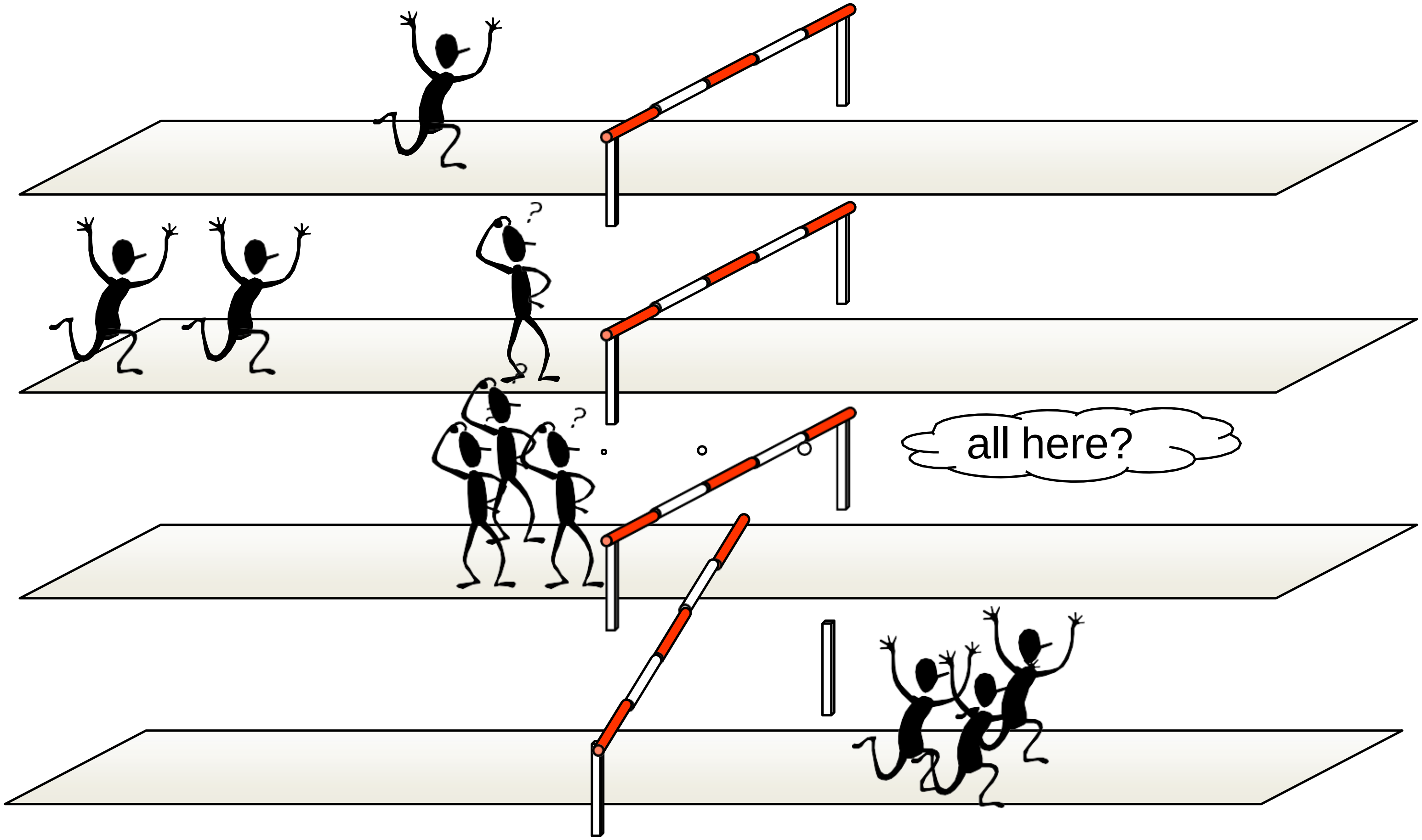
OpenMP - Synchronization Constructs

- When a **BARRIER directive** is **reached**, a **thread will wait** at that **point until** all other **threads have reached that barrier**

- ***All threads then resume executing in parallel the code that follows the barrier.***

```
#pragma omp barrier
...
```

Barrier Synchronization



Demo: Barrier.c

Reduction (Data-sharing Attribute Clause)

- The **REDUCTION** **clause** **performs** a **reduction operation** on the **variables** that **appear in the list**
- A **private copy** for **each list variable** is **created** and **initialized** for **each thread**
- At the **end of the reduction**, the **reduction variable (all private copies)** **is examined and the shared variable's final result** is **written.**

```
#pragma omp operator: list
...
```

operator can be `+,-,*,&&,||,max,min` ...

Reduction (Data-sharing Attribute Clause)

```
int main(int argc, char* argv[])
{
   srand(time(NULL));
   int winner;
   #pragma omp parallel reduction(max:winner) num_threads(10)
   {
        winner = (rand() % 1000) + omp_get_thread_num();
        printf("Thread: %d has Chosen: %d\n",
omp_get_thread_num(),winner);
   }
   printf("Winner: %d\n", winner);

}
```

Demo: Reduction.c

Any Questions?