

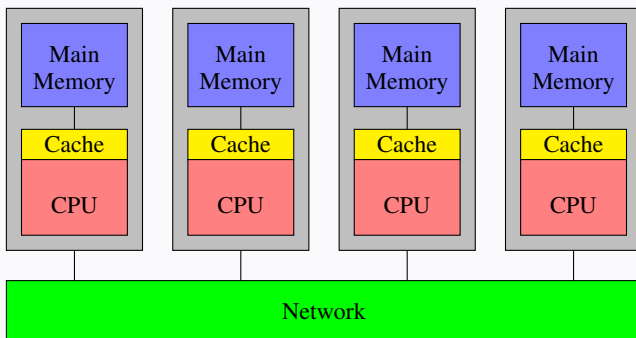
Introduction to OpenMP

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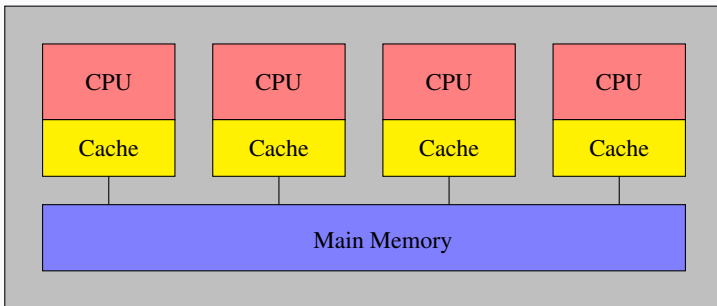
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LONI Parallel Programming Workshop
Louisiana State University
Baton Rouge
June 2-4, 2014

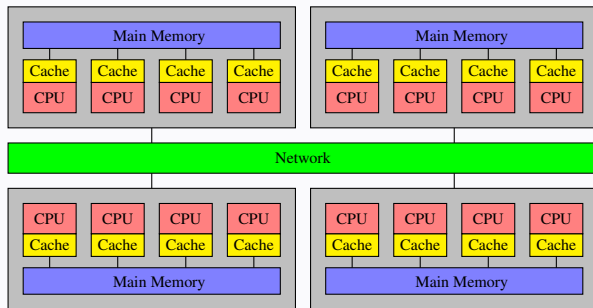
- Each process has its own address space
 - Data is local to each process
- Data sharing is achieved via explicit message passing
- Example
 - MPI



- All threads can access the global memory space.
- Data sharing achieved via writing to/reading from the same memory location
- Example
 - OpenMP
 - Pthreads



- The shared memory model is most commonly represented by Symmetric Multi-Processing (SMP) systems
 - Identical processors
 - Equal access time to memory
- Large shared memory systems are rare, clusters of SMP nodes are popular.



Shared Memory

- Pros
 - Global address space is user friendly
 - Data sharing is fast
- Cons
 - Lack of scalability
 - Data conflict issues

Distributed Memory

- Pros
 - Memory scalable with number of processors
 - Easier and cheaper to build
- Cons
 - Difficult load balancing
 - Data sharing is slow

Compiler Flags for Automatic Parallelization

GCC -floop-parallelize-all

Intel -parallel

XL -qsmp=auto

PGI -Mconcur=<flags>

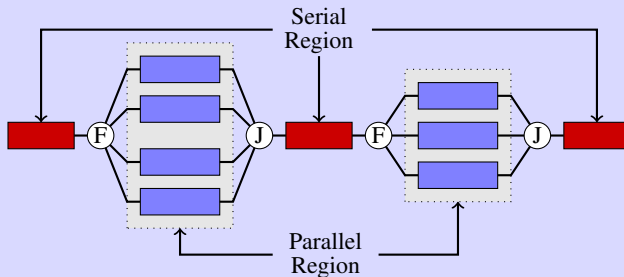
When to consider using OpenMP?

- The compiler may not be able to do the parallelization
 - ❶ A loop is not parallelized
 - The data dependency analysis is not able to determine whether it is safe to parallelize or not
 - ❷ The granularity is not high enough
 - The compiler lacks information to parallelize at the highest possible level

- OpenMP is an Application Program Interface (API) for thread based parallelism; Supports Fortran, C and C++
- Uses a fork-join execution model
- OpenMP structures are built with program directives, runtime libraries and environment variables
- OpenMP has been the industry standard for shared memory programming over the last decade
 - Permanent members of the OpenMP Architecture Review Board: AMD, Cray, Fujitsu, HP, IBM, Intel, Microsoft, NEC, PGI, SGI, Sun
- OpenMP 3.1 was released in September 2011

- Portability
 - Standard among many shared memory platforms
 - Implemented in major compiler suites
- Ease to use
 - Serial programs can be parallelized by adding compiler directives
 - Allows for incremental parallelization - a serial program evolves into a parallel program by parallelizing different sections incrementally

- Parallelism is achieved by generating multiple threads that run in parallel
 - A fork (F) is when a single thread is made into multiple, concurrently executing threads
 - A join (J) is when the concurrently executing threads synchronize back into a single thread
- OpenMP programs essentially consist of a series of forks and joins.



- Program directives
 - Syntax
 - C/C++: `#pragma omp <directive> [clause]`
 - Fortran: `!$omp <directive> [clause]`
 - Parallel regions
 - Parallel loops
 - Synchronization
 - Data Structure
 - ...
- Runtime library routines
- Environment variables

- Fortran: case insensitive
 - Add: `use omp_lib` or `include "omp_lib.h"`
 - Usage: **Sentinel directive** [clauses]
 - Fortran 77
 - **Sentinel** could be: `!$omp`, `*$omp`, `c$omp` and must begin in first column
 - Fortran 90/95/2003
 - **Sentinel**: `!$omp`
 - End of parallel region is signified by the end sentinel statement: **`!$omp end directive`** [clauses]
- C/C++: case sensitive
 - Add `#include <omp.h>`
 - Usage: **`#pragma omp directive`** [clauses] newline

- Parallel Directive
 - **parallel**
- Worksharing Constructs
 - Fortran: **do, workshare**
 - C/C++: **for**
 - Fortran/C/C++: **sections**
- Synchronization
 - **master, single, ordered, flush, atomic**

- `private(list), shared(list)`
- `firstprivate(list), lastprivate(list)`
- `reduction(operator:list)`
- `schedule(method[,chunk_size])`
- `nowait`
- `if(scalar_expression)`
- `num_thread(num)`
- `threadprivate(list), copyin(list)`
- `ordered`
- `more . . .`

- Number of Threads: `omp_{set,get}_num_threads`
- Thread ID: `omp_get_thread_num`
- Scheduling: `omp_{set,get}_dynamic`
- Nested Parallelism: `omp_in_parallel`
- Locking: `omp_{init,set,unset}_lock`
- Wallclock Timer: `omp_get_wtime`
- more . . .

- OMP_NUM_THREADS
- OMP_SCHEDULE
- OMP_STACKSIZE
- OMP_DYNAMIC
- OMP_NESTED
- OMP_WAIT_POLICY
- more . . .

- The **parallel** directive forms a team of threads for parallel execution.
- Each thread executes the block of code within the OpenMP Parallel region.

C

```
#include <stdio.h>

int main() {

#pragma omp parallel
{
    printf("Hello world\n");
}

}
```

Fortran

```
program hello

    implicit none

    !$omp parallel
    print *, 'Hello World'
    !$omp end parallel

end program hello
```


- IBM Power7 clusters

- Use thread-safe compilers (with "_r")
- Use '-qsmp=omp' option

```
% xlc_r -qsmp=omp hello.c && OMP_NUM_THREADS=4 ./a.out
```

```
% xlf90_r -qsmp=omp hello.f90 && OMP_NUM_THREADS=4 ./a.out
```

- Dell Linux clusters

- Use '-openmp' option (Intel compiler)
- Use '-fopenmp' option (GNU compiler)
- Use '-mp' option (PGI Compiler)

```
% icc -openmp hello.c && OMP_NUM_THREADS=4 ./a.out
```

```
% ifort -openmp hello.f90 && OMP_NUM_THREADS=4 ./a.out
```

```
altair:openmp apacheco$ gcc -fopenmp helloworld.c -o helloc.x
altair:openmp apacheco$ gfortran -fopenmp helloworld.f90 -o hellof90.x
altair:openmp apacheco$ OMP_NUM_THREADS=4 ./helloc.x
Hello world
Hello world
Hello world
Hello world
altair:openmp apacheco$ OMP_NUM_THREADS=4 ./hellof90.x
Hello World
Hello World
Hello World
Hello World
```

```
#include <omp.h>
#include <stdio.h>
int main () {
    #pragma omp parallel
    {
        printf("Hello from thread %d out of %d
            threads\n",omp_get_thread_num() ,
                omp_get_num_threads() );
    }
    return 0;
}
```

OpenMP include file

Parallel region starts here

Runtime library functions

Parallel region ends here

Output

```
Hello from thread 0 out of 4 threads
Hello from thread 1 out of 4 threads
Hello from thread 2 out of 4 threads
Hello from thread 3 out of 4 threads
```

```
program hello
```

```
implicit none
```

```
integer :: omp_get_thread_num, omp_get_num_threads
```

```
!$omp parallel
```

```
print *, 'Hello from thread',omp_get_thread_num() , &  
      'out of ' ,omp_get_num_threads(), ' threads'
```

```
!$omp end parallel
```

```
end program hello
```

Parallel region starts here

Runtime library functions

Parallel region ends here

Output

```
Hello from thread 0 out of 4 threads  
Hello from thread 1 out of 4 threads  
Hello from thread 2 out of 4 threads  
Hello from thread 3 out of 4 threads
```

- Write a “hello world” program with OpenMP where
 - If the thread id is odd, then print a message "Hello world from thread x, I'm odd!"
 - If the thread id is even, then print a message "Hello world from thread x, I'm even!"

C

```
#include <stdio.h>
/* Include omp.h ? */
int main() {
    int id;
    /* Add Ompem pragma */
    {
        id = /* Get Thread ID */
        if (id%2==1)
            printf("Hello world from thread %d,
                I am odd\n", id);
        else
            printf("Hello world from thread %d,
                I am even\n", id);
    }
}
```

Fortran

```
program hello
    ! Include/Use omp_lib.h/omp_lib ?
    implicit none
    integer i
    ! Add OMP Directive
    i = ! Get Thread ID
    if (mod(i,2).eq.1) then
        print *, 'Hello from thread', i, ', I am
            odd!'
    else
        print *, 'Hello from thread', i, ', I am
            even!'
    endif
    ! End OMP Directive ?
end program hello
```

C/C++

```
#include <omp.h>
#include <stdio.h>
int main() {
    int id;
    #pragma omp parallel private(id)
    {
        id = omp_get_thread_num();
        if (id%2==1)
            printf("Hello world from thread %d,
                I am odd\n", id);
        else
            printf("Hello world from thread %d,
                I am even\n", id);
    }
}
```

```
altair:solution apacheco$ gcc -fopenmp -o helloc hello.c
altair:solution apacheco$ ./helloc
Hello world from thread 1, I am odd
Hello world from thread 2, I am even
Hello world from thread 0, I am even
Hello world from thread 3, I am odd
```

Fortran

```
program hello
    use omp_lib
    implicit none
    integer i
    !$omp parallel private(i)
    i = omp_get_thread_num()
    if (mod(i,2).eq.1) then
        print *, 'Hello from thread', i, ', I am
            odd!'
    else
        print *, 'Hello from thread', i, ', I am
            even!'
    endif
    !$omp end parallel
end program hello
```

```
altair:solution apacheco$ gfortran -fopenmp -o hellof hello.f90
altair:solution apacheco$ ./hellof
Hello from thread      2 , I am even!
Hello from thread      1 , I am odd!
Hello from thread      0 , I am even!
Hello from thread      3 , I am odd!
```

- We need to share work among threads to achieve parallelism
- Syntax:
 - Fortran: `!$omp parallel`
 - C/C++: `#pragma for`
- Loops are the most likely targets when parallelizing a serial program
- Syntax:
 - Fortran: `!$omp do`
 - C/C++: `#pragma omp for`
- Other work sharing directives available
 - Sections: `!$omp sections` or `#pragma sections`
 - Tasks: `!$omp task` or `#pragma omp task`
- The parallel and work sharing directive can be combined as
 - `!$omp parallel do`
 - `#pragma omp parallel sections`

C/C++

```
#include <omp.h>

int main() {
    int i = 0, n = 100, a[100];
    #pragma omp parallel for
    for (i = 0; i < n ; i++) {
        a[i] = (i+1) * (i+2) ;
    }
}
```

Fortran

```
program paralleldo

    implicit none
    integer :: i, n, a(100)

    i = 0
    n = 100
    !$omp parallel
    !$omp do
    do i = 1, n
        a(i) = i * (i+1)
    end do
    !$omp end do
    !$omp end parallel
end program paralleldo
```

- OpenMP provides different methods to divide iterations among threads, indicated by the `schedule` clause
 - Syntax: `schedule (<method>, [chunk size])`
- Methods include
 - `Static`: the default schedule; divide iterations into chunks according to `size`, then distribute chunks to each thread in a round-robin manner.
 - `Dynamic`: each thread grabs a chunk of iterations, then requests another chunk upon completion of the current one, until all iterations are executed.
 - `Guided`: similar to `Dynamic`; the only difference is that the chunk size starts large and shrinks to `size` eventually.

4 threads, 100 iterations

Schedule	Iterations mapped onto thread			
	0	1	2	3
Static	1-25	26-50	51-75	76-100
Static, 20	1-20, 81-100	21-40	41-60	61-80
Dynamic	1,...	2,...	3,...	4,...
Dynamic, 10	1 - 10,...	11 - 20,...	21 - 30,...	31 - 40,...

Schedule	When to Use
Static	Even and predictable workload per iteration; scheduling may be done at compilation time, least work at runtime.
Dynamic	Highly variable and unpredictable workload per iteration; most work at runtime
Guided	Special case of dynamic scheduling; compromise between load balancing and scheduling overhead at runtime

- Gives a different block to each thread

C/C++

```
#pragma omp parallel
{
  #pragma omp sections
  {
    #pragma omp section
    some_calculation();
    #pragma omp section
    some_more_calculation();
    #pragma omp section
    yet_some_more_calculation();
  }
}
```

Fortran

```
!$omp parallel
!$omp sections
!$omp section
call some_calculation
!$omp section
call some_more_calculation
!$omp section
call yet_some_more_calculation
!$omp end sections
!$omp end parallel
```

- `Shared(list)`
 - Specifies the variables that are shared among all threads
- `Private(list)`
 - Creates a local copy of the specified variables for each thread
 - the value is uninitialized!
- `Default(shared|private|none)`
 - Defines the default scope of variables
 - **C/C++ API does not have default (private)**
- Most variables are shared by default
 - A few exceptions: iteration variables; stack variables in subroutines; automatic variables within a statement block.

- SAXPY is a common operation in computations with vector processors included as part of the BLAS routines
$$y \leftarrow \alpha x + y$$
- SAXPY is a combination of scalar multiplication and vector addition
- Parallelize the following SAXPY code

C

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

int main() {
    int i;
    long long int n=100000000;
    float a=2.0;
    float x[n];
    float y[n];
    clock_t start_time, end_time;

    /* Parallelize this block of code (optional) */
    for (i = 0; i < n; i++) {
        x[i] = 1.0;
        y[i] = 2.0;
    }

    start_time = clock();
    /* Parallelize this block of code */
    for (i = 0; i < n; i++) {
        y[i] = a*x[i] + y[i];
    }
    end_time = clock();
    printf ("SAXPY Time: %f\n", (double)(end_time - start_time)/
        CLOCKS_PER_SEC);
}
```

Fortran

```
program saxpy

    implicit none
    integer :: i,n
    real,dimension(:),allocatable :: x, y
    real :: a,start_time, end_time

    n=100000000
    allocate(x(n),y(n))
    ! Parallelize this block of code (optional)
    x = 1.0d0
    y = 2.0d0
    a = 2.0d0

    call cpu_time(start_time)
    ! Parallelize this block of code
    do i = 1, n
        y(i) = y(i) + a * x(i)
    end do
    call cpu_time(end_time)
    deallocate(x,y)

    print ' (a,f8.6)', 'SAXPY Time: ', end_time - start_time

end program saxpy
```

C

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

int main() {
    long long int i, n=500000000;
    float a=2.0;
    float x[n];
    float y[n];
    double start_time, end_time;

    for (i = 0; i < n; i++){
        x[i] = 1.0;
        y[i] = 2.0;
    }

    start_time = omp_get_wtime();
    #pragma omp parallel for private(i)
    for (i = 0; i < n; i++){
        y[i] = a*x[i] + y[i];
    }
    end_time = omp_get_wtime();
    printf ("SAXPY Time: %f\n", end_time - start_time);
}
```

Fortran

```
program saxpy

    implicit none
    integer, parameter :: dp = selected_real_kind(15)
    integer, parameter :: ip = selected_int_kind(15)
    integer(ip) :: i,n
    real(dp),dimension(:),allocatable :: x, y
    real(dp) :: a,start_time, end_time

    n=500000000
    allocate(x(n),y(n))
    !$omp parallel sections
    !$omp section
    x = 1.0
    !$omp section
    y = 1.0
    !$omp end parallel sections
    a = 2.0

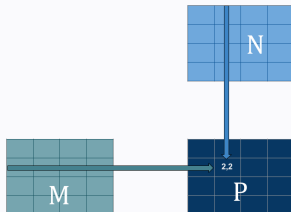
    call cpu_time(start_time)
    !$omp parallel do default(shared) private(i)
    do i = 1, n
        y(i) = y(i) + a * x(i)
    end do
    !$omp end parallel do
    call cpu_time(end_time)
    deallocate(x,y)

    print '(a,f8.6)', 'SAXPY Time: ', end_time - start_time

end program saxpy
```

Language	Serial	OpenMP (16 Threads)	SpeedUp
C	0.511	0.186	2.75
Fortran	0.993	0.244	4.07

- Most Computational code involve matrix operations such as matrix multiplication.
- Consider a matrix **C** of two matrices **A** and **B**:
Element i,j of **C** is the dot product of the i^{th} row of **A** and j^{th} column of **B**



● Parallelize the following MATMUL code

C

```
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

#define dt(start, end) ((end.tv_sec - start.tv_sec) + \
    1/1000000.0*(end.tv_usec - start.tv_usec))

int main() {
    int i,j,k;
    int nra=1500, nca=2000, ncb=1000;
    double a[nra][nca], b[nca][ncb], c[nra][ncb];
    struct timeval icalc, scalc, ecalc;
    double flops, sum, timing;

    flops = 2.0 * nra * nca * ncb;

    gettimeofday(&icalc, NULL);
    for (i = 0; i < nra; i++) {
        for (j = 0; j < nca; j++) {
            a[i][j] = (double) (i+j);
        }
    }
    for (j = 0; j < nca; j++) {
        for (k = 0; k < ncb; k++) {
            b[j][k] = (double) (i+j);
        }
    }
    for (i = 0; i < nra; i++) {
        for (k = 0; k < ncb; k++) {
            c[i][k] = 0.0;
        }
    }

    gettimeofday(&scalc, NULL);
    /* Parallelize the following block of code */
    for (i = 0; i < nra; i++) {
        for (k = 0; k < ncb; k++) {
            sum = 0.0;
            for (j = 0; j < nca; j++) {
                sum = sum + a[i][j] * b[j][k];
            }
            c[i][k] = sum;
        }
    }
    gettimeofday(&ecalc, NULL);

    timing = dt(scalc, ecalc);
    printf("Init Time: %6.3f Calc Time: %6.3f GFlops: %7.3f\n", dt(icalc,
        scalc), timing, 1e-9*flops/timing);
}
```

Fortran

```
program matrix_mul

implicit none

integer, parameter :: dp = selected_real_kind(14)
integer :: i,j,k
integer, parameter :: nra=1500, nca=2000, ncb=1000
real(dp) :: a(nra,nca), b(nca,ncb), c(nra,ncb)
real(dp) :: flops, sum
real(dp) :: init_time, start_time, end_time

flops = 2d0 * float(nra) * float(nca) * float(ncb)

call cpu_time(init_time)
c = 0d0

do i = 1, nra
    do j = 1, nca
        a(i,j) = i + j
    end do
end do

do i = 1, nca
    do j = 1, ncb
        b(i,j) = i * j
    end do
end do

call cpu_time(start_time)
! Parallelize the following block of code
do j = 1, nca
    do k = 1, ncb
        sum = 0d0
        do i = 1, nra
            sum = sum + a(i,j) * b(j,k)
        end do
        c(i,k) = sum
    end do
end do
call cpu_time(end_time)

print '(a,f6.3,a,f6.3,a,f7.3)', 'Init Time: ', start_time - init_time,
    &
    ' Calc Time: ', end_time - start_time, &
    ' GFlops: ', 1d-9 * flops / (end_time - start_time)

end program matrix_mul
```


C

```

#include <stdio.h>
#include <stdlib.h>
#include <time.h>

#define dt(start, end) ((end.tv_sec - start.tv_sec) + \
    1/1000000.0*(end.tv_usec - start.tv_usec))

int main() {
    int i,j,k;
    int nra=1500, nca=2000, ncb=1000;
    double a[nra][nca], b[nca][ncb], c[nra][ncb];
    struct timeval icalc, scalc, ecalc;
    double flops, sum, timing;

    flops = 2.0 * nra * nca * ncb;

    gettimeofday(&icalc, NULL);
    for (i = 0; i < nra; i++) {
        for (j = 0; j < nca; j++) {
            a[i][j] = (double)(i+j);
        }
    }
    for (j = 0; j < nca; j++) {
        for (k = 0; k < ncb; k++) {
            b[j][k] = (double)(i+j);
        }
    }
    for (i = 0; i < nra; i++) {
        for (k = 0; k < ncb; k++) {
            c[i][k] = 0.0;
        }
    }

    gettimeofday(&scalc, NULL);
    #pragma omp parallel for private(sum,i,k,j)
    for (i = 0; i < nra; i++) {
        for (k = 0; k < ncb; k++) {
            sum = 0.0;
            for (j = 0; j < nca; j++) {
                sum = sum + a[i][j] * b[j][k];
            }
            c[i][k] = sum;
        }
    }
    gettimeofday(&ecalc, NULL);

    timing = dt(scalc, ecalc);
    printf("Init Time: %6.3f Calc Time: %6.3f GFlops: %7.3f\n", dt(icalc,
        scalc), timing, 1e-9*flops/timing);
}

```

Fortran

```

program matrix_mul

implicit none

integer, parameter :: dp = selected_real_kind(14)
integer :: i,j,k
integer, parameter :: nra=1500, nca=2000, ncb=1000
real(dp) :: a(nra,nca), b(nca,ncb), c(nra,ncb)
real(dp) :: flops, sum
real(dp) :: init_time, start_time, end_time
integer, dimension(8) :: value

flops = 2d0 * float(nra) * float(nca) * float(ncb)

call date_and_time(VALUES=value)
init_time = float(value(6))*60 + float(value(7)) + float(value(8))/1000
c = 0d0

do i = 1, nra
    do j = 1, nca
        a(i,j) = i + j
    end do
end do

do i = 1, nca
    do j = 1, ncb
        b(i,j) = i * j
    end do
end do

call date_and_time(VALUES=value)
start_time = float(value(6))*60 + float(value(7)) + float(value(8))/1000
do i = 1, nra
    do k = 1, ncb
        sum = 0d0
        do i = 1, nra
            sum = sum + a(i,j) * b(j,k)
        end do
        c(i,k) = sum
    end do
end do
!$omp end parallel do
call date_and_time(VALUES=value)
end_time = float(value(6))*60 + float(value(7)) + float(value(8))/1000d0

print '(a,f6.3,a,f6.3,a,f7.3)', 'Init Time: ', start_time - init_time,
    &
    ' Calc Time: ', end_time - start_time, &
    ' GFlops: ', 1d-9 * flops/(end_time - start_time)

end program matrix_mul

```

- Array elements that are in the same cache line can lead to false sharing.
 - The system handles cache coherence on a cache line basis, not on a byte or word basis.
 - Each update of a single element could invalidate the entire cache line.

```
!$omp parallel
myid = omp_get_thread_num()
nthreads = omp_get_numthreads()
do i = myid+1, n , nthreads
  a(i) = some_function(i)
end do
!$omp end parallel
```

- Multiple threads try to write to the same memory location at the same time.
 - Indeterministic results
- Inappropriate scope of variable can cause indeterministic results too.
- When having indeterministic results, set the number of threads to 1 to check
 - If problem persists: scope problem
 - If problem is solved: race condition

```
!$omp parallel do
do i = 1, n
  if (a(i) > max) then
    max = a(i)
  end if
end do
!$omp end parallel do
```

- “Stop sign” where every thread waits until all threads arrive.
- Purpose: protect access to shared data.
- Syntax:
 - Fortran: `!$omp barrier`
 - C/C++: `#pragma omp barrier`
- A barrier is implied at the end of every parallel region
 - Use the `nowait` clause to turn it off
- Synchronizations are costly so their usage should be minimized.

- Critical: Only one thread at a time can enter a critical region

```
!$omp parallel do
do i = 1, n
  b = some_function(i)
  !$omp critical
  call some_routine(b,x)
end do
!$omp end parallel do
```

- Atomic: Only one thread at a time can update a memory location

```
!$omp parallel do
do i = 1, n
  b = some_function(i)
  !$omp atomic
  x = x + b
end do
!$omp end parallel do
```

- Not initialized at the beginning of parallel region.
- After parallel region
 - Not defined in OpenMP 2.x
 - 0 in OpenMP 3.x

tmp not initialized here

```
void wrong()
{
    int tmp = 0;
    #pragma omp for private( tmp )
    for (int j = 0; j < 100; ++j)
        tmp += j
    printf("%d\n", tmp )
}
```

OpenMP 2.5: tmp undefined

OpenMP 3.0: tmp is 0

- Firstprivate
 - Initialize each private copy with the corresponding value from the master thread
- Lastprivate
 - Allows the value of a private variable to be passed to the shared variable outside the parallel region

tmp initialized as 0

```
void wrong()
{
    int tmp = 0;
    #pragma omp for firstprivate( tmp ) lastprivate( tmp )
    for (int j = 0; j < 100; ++j)
        tmp += j
    printf("%d\n", tmp )
}
```

The value of tmp is the value when j=99

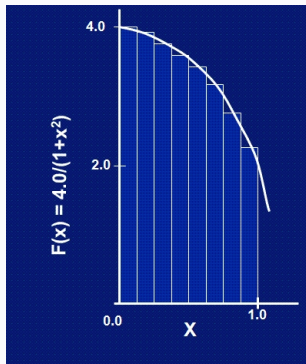
- We know that

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

- So numerically, we can approximate pi as the sum of a number of rectangles

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

Meadows et al, A “hands-on” introduction to OpenMP, SC09



C/C++

```
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

int main() {
    int i;
    long long int n=100000000;
    clock_t start_time, end_time;
    double x, pi;
    double sum = 0.0;
    double step = 1.0/(double) n;

    start_time = clock();
    /* Parallelize the following block of code */
    for (i = 0; i < n; i++) {
        x = (i+0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
    }
    pi = step * sum;
    end_time = clock();

    printf("pi = %17.15f\n", pi);
    printf("time to compute = %g seconds\n", (double)
        (end_time - start_time)/CLOCKS_PER_SEC);
    return 0;
}
```

Fortran

```
program pi_serial

    implicit none
    integer, parameter :: dp=selected_real_kind(14)
    integer :: i
    integer, parameter :: n=100000000
    real(dp) :: x, pi, sum, step, start_time, end_time

    sum = 0d0
    step = 1.d0/float(n)

    call cpu_time(start_time)
    ! Parallelize the following block of code
    do i = 0, n
        x = (i + 0.5d0) * step
        sum = sum + 4.d0 / (1.d0 + x ** 2)
    end do
    pi = step * sum
    call cpu_time(end_time)

    print '(a,f17.15)', "pi = ", pi
    print '(a,f9.6,a)', "time to compute =", end_time
        - start_time, " seconds"

end program pi_serial
```

C/C++

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

int main() {
    long long int i, n=10000000000;
    double start_time, end_time;
    double x, pi;
    double sum = 0.0;
    double step = 1.0/(double) n;

    start_time = omp_get_wtime();
    #pragma omp parallel for default(shared) private(i,
        x)
        for (i = 0; i < n; i++) {
            x = (i+0.5)*step;
    #pragma omp atomic
        sum += 4.0/(1.0+x*x);
    }
    pi = step * sum;
    end_time = omp_get_wtime();

    printf("pi = %17.15f\n", pi);
    printf("time to compute = %g seconds\n", (double)
        (end_time - start_time));
    return 0;
}
```

Fortran

```
program pi_omp

    implicit none
    integer, parameter :: dp=selected_real_kind(14)
    integer, parameter :: ip=selected_int_kind(15)
    integer(ip) :: i
    integer(ip), parameter :: n=10000000000
    real(dp) :: x, pi, sum, step, start_time, end_time
    integer, dimension(8) :: value

    sum = 0d0
    step = 1.d0/float(n)

    call date_and_time(VALUEs=value)
    start_time = float(value(6)*60) + float(value(7))
        + float(value(8))/1000d0
    !$omp parallel do default(shared) private(i,x)
    do i = 0, n
        x = (i + 0.5d0) * step
        !$omp atomic
        sum = sum + 4.d0 / (1.d0 + x ** 2)
    end do
    !$omp end parallel do
    pi = step * sum
    call date_and_time(VALUEs=value)
    end_time = float(value(6)*60) + float(value(7)) +
        float(value(8))/1000d0
    if ( start_time > end_time ) end_time = end_time
        + 3600d0

    print '(a,f17.15)', "pi = ", pi
    print '(a,f9.3,a)', "time to compute =", end_time
        - start_time, " seconds"
```

```
altair:openmp apacheco$ gcc pi_serial.c -o pic
altair:openmp apacheco$ gcc -fopenmp pi_ompl.c -o pic_omp
altair:openmp apacheco$ gfortran pi_serial.f90 -o pif
altair:openmp apacheco$ gfortran -fopenmp pi_ompl.f90 -o pif_omp
altair:solution apacheco$ echo ``Serial C Code``; ./pic
Serial C Code
pi = 3.141592653590426
time to compute = 1.72441 seconds
altair:solution apacheco$ echo ``OMP C Code with Atomic``; ./pic_omp
OMP C Code with Atomic
pi = 3.141592653590195
time to compute = 6.10142 seconds
altair:solution apacheco$ echo ``Serial F90 Code``; ./pif
Serial F90 Code
pi = 3.141592673590427
time to compute = 0.988196 seconds
altair:solution apacheco$ echo ``OMP F90 Code with Atomic``; ./pif_omp
OMP F90 Code with Atomic
pi = 3.141592673590174
time to compute = 7.368610 seconds
```

- What is the value of pi if you did not have the *atomic* directive?

- The `reduction` clause allows accumulative operations on the value of variables.
- Syntax: `reduction (operator:variable list)`
- A private copy of each variable which appears in `reduction` is created as if the `private` clause is specified.
- Operators
 - 1 Arithmetic
 - 2 Bitwise
 - 3 Logical

C/C++

```
#include <omp.h>
int main() {
    int i, n = 100, sum, a[100], b[100];
    for (i = 0; i < n; i++) {
        a[i] = i;
        b[i] = 1;
    }
    sum = 0;
    #pragma omp parallel for reduction(+:sum)
    for (i = 0; i < n; i++) {
        sum += a[i] * b[i];
    }
}
```

Fortran

```
program reduction

    implicit none
    integer :: i, n, sum, a(100), b(100)

    n = 100 ; b = 1; sum = 0
    do i = 1, n
        a(i) = i
    end do
    !$omp parallel do reduction(+:sum)
    do i = 1, n
        sum = sum + a(i) * b(i)
    end do
    !$omp end parallel do

end program reduction
```

- Redo exercise 2 with reduction

C

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

int main() {
    long long int i, n=10000000000;
    double start_time, end_time;
    double x, pi;
    double sum = 0.0;
    double step = 1.0/(double) n;

    start_time = omp_get_wtime();
    #pragma omp parallel default(shared) private(i,
        x) reduction(+:sum)
    {
        #pragma omp for
        for (i = 0; i < n; i++) {
            x = (i+0.5)*step;
            sum += 4.0/(1.0+x*x);
        }
    }
    pi = step * sum;
    end_time = omp_get_wtime();

    printf("pi = %17.15f\n",pi);
    printf("time to compute = %g seconds\n", (
        double)(end_time - start_time));
    return 0;
}
```

Fortran

```
program pi_omp

    implicit none
    integer, parameter :: dp=selected_real_kind(1
        4)
    integer, parameter :: ip=selected_int_kind(15
        )
    integer(ip) :: i
    integer(ip), parameter :: n=10000000000
    real(dp) :: x,pi,sum,step,start_time,end_time
    integer, dimension(8) :: value

    sum = 0d0
    step = 1.d0/float(n)

    call date_and_time(VALUE=value)
    start_time = float(value(6)*60) + float(value
        (7)) + float(value(8))/1000d0
    !$omp parallel do default(shared) private(i,x
        ) reduction(+:sum)
    do i = 0, n
        x = (i + 0.5d0) * step
        sum = sum + 4.d0 / (1.d0 + x ** 2)
    end do
    !$omp end parallel do
    pi = step * sum
    call date_and_time(VALUE=value)
    end_time = float(value(6)*60) + float(value(7
        )) + float(value(8))/1000d0
    if ( start_time > end_time ) end_time =
        end_time + 3600d0

    print '(a,f17.15)', "pi = ", pi
    print '(a,f9.3,a)', "time to compute =",
```

end program pi_omp

```
altair:openmp apacheco$ gcc -fopenmp pi_omp.c -o pic_ompr
altair:openmp apacheco$ gfortran -fopenmp pi_omp.f90 -o pif_ompr
altair:solution apacheco$ echo ``Serial C Code``; ./pic
Serial C Code
pi = 3.141592653590426
time to compute = 1.72441 seconds
altair:solution apacheco$ echo ``OMP C Code with Atomic``; ./pic_omp
OMP C Code with Atomic
pi = 3.141592653590195
time to compute = 6.10142 seconds
altair:solution apacheco$ echo ``OMP C Code with Reduction``; ./pic_ompr
OMP C Code with Reduction
pi = 3.141592653589683
time to compute = 0.48712 seconds
altair:solution apacheco$ echo ``Serial F90 Code``; ./pif
Serial F90 Code
pi = 3.141592673590427
time to compute = 0.988196 seconds
altair:solution apacheco$ echo ``OMP F90 Code with Atomic``; ./pif_omp
OMP F90 Code with Atomic
pi = 3.141592673590174
time to compute = 7.368610 seconds
altair:solution apacheco$ echo ``OMP F90 Code with Reduction``; ./pif_ompr
OMP F90 Code with Reduction
pi = 3.141592673589683
time to compute = 0.400939 seconds
```


- Modify/query the number of threads
 - `omp_set_num_threads()`, `omp_get_num_threads()`,
`omp_get_thread_num()`, `omp_get_max_threads()`
- Query the number of processors
 - `omp_num_procs()`
- Query whether or not you are in an active parallel region
 - `omp_in_parallel()`
- Control the behavior of dynamic threads
 - `omp_set_dynamic()`, `omp_get_dynamic()`

- OMP_NUM_THREADS: set default number of threads to use.
- OMP_SCHEDULE: control how iterations are scheduled for parallel loops.

- https://docs.loni.org/wiki/Using_OpenMP
- <http://en.wikipedia.org/wiki/OpenMP>
- <http://www.nersc.gov/nusers/help/tutorials/openmp>
- <http://www.llnl.gov/computing/tutorials/openMP>
- <http://www.citutor.org>