Introduction to OpenMP

Alexander B. Pacheco

User Services Consultant
LSU HPC & LONI
sys-help@loni.org

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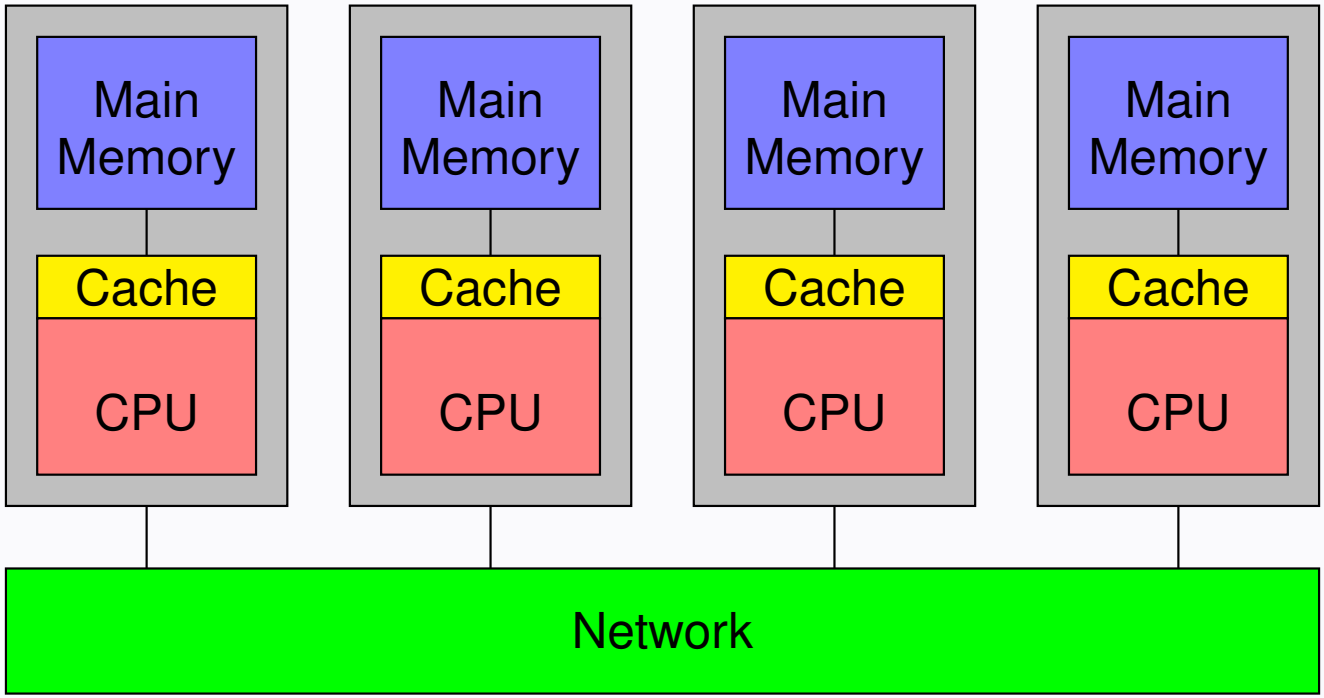
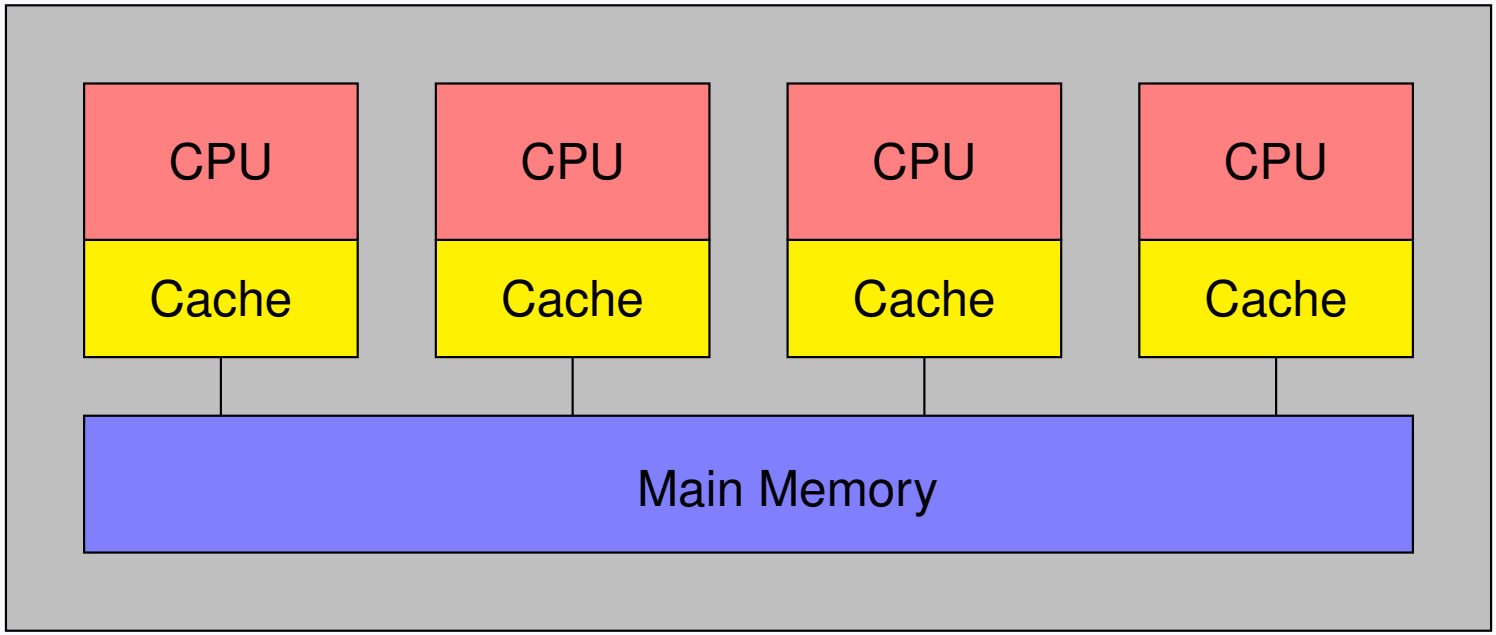
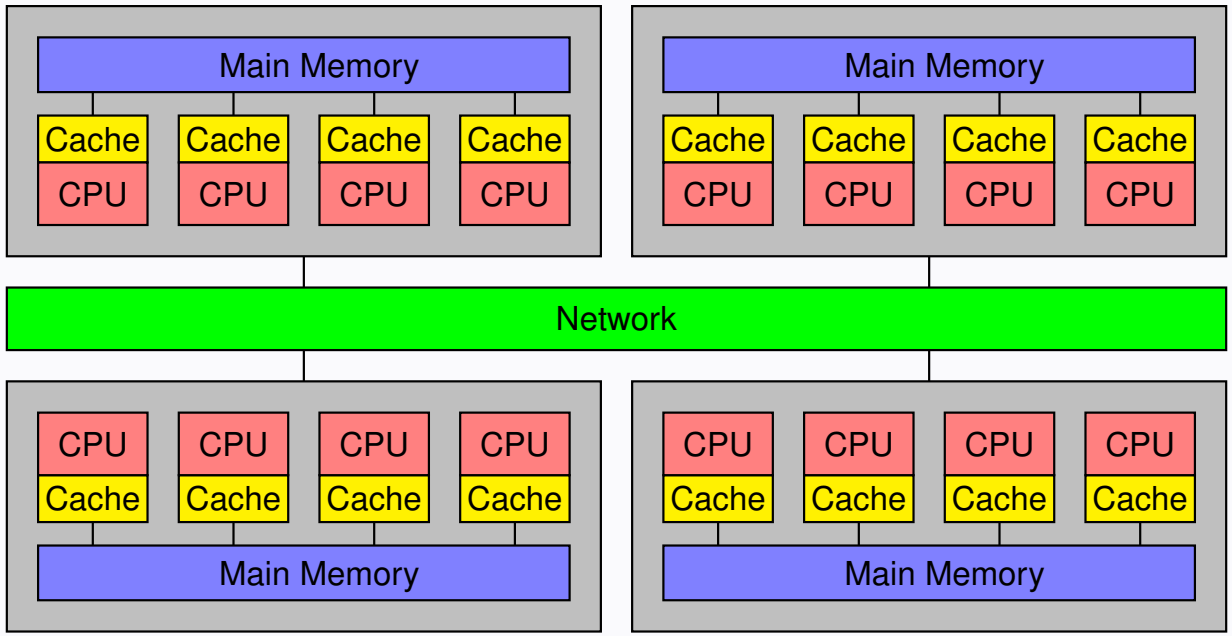
- Each process has its own address space
  - Data is local to each process
- Data sharing is achieved via explicit message passing
- Example
  - MPI



- 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>

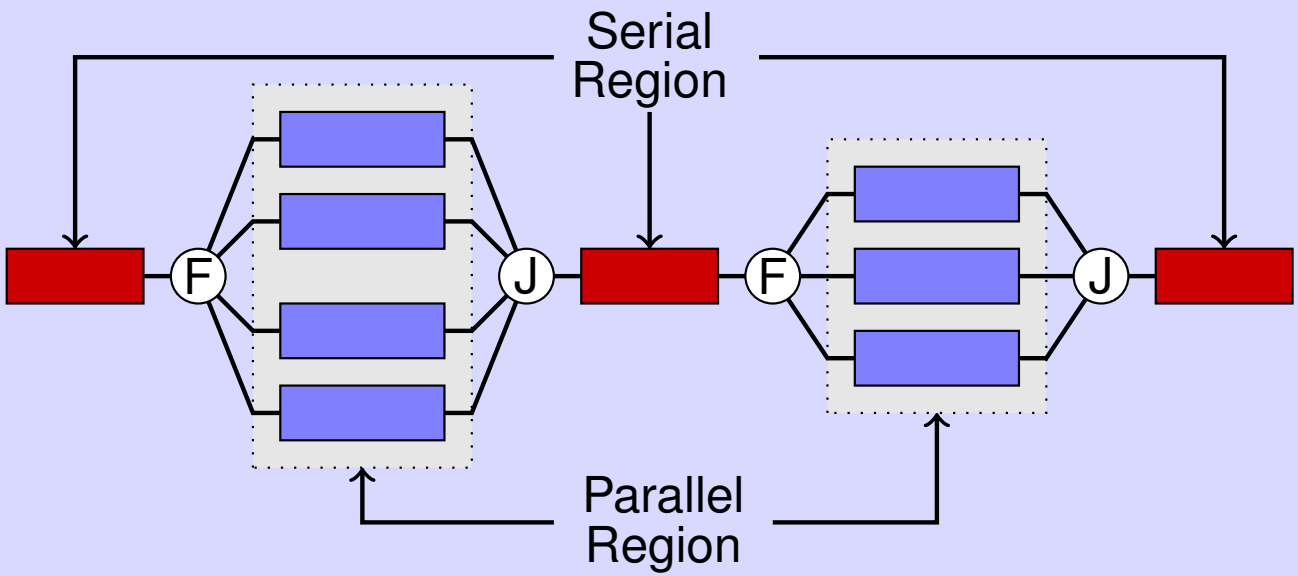
When to consider using OpenMP?

- The compiler may not be able to do the parallelization
  1. A loop is not parallelized
     - The data dependency analysis is not able to determine whether it is safe to parallelize or not
  2. 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, Fujutsu, 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

```c
#include <stdio.h>

int main() {

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

}
```

Fortran

```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
  1. If the thread id is odd, then print a message "Hello world from thread x, I’m odd!”
  2. If the thread id is even, then print a message "Hello world from thread x, I’m even!”

C

```c
#include <stdio.h>
/* Include omp.h ? */
int main() {
  int id;
  /* Add Opemp 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

```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++

```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

```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++

```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

```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 interations 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`	$1, \cdots$	$2, \cdots$	$3, \cdots$	$4, \cdots$
`Dynamic,10`	$1-10, \cdots$	$11-20, \cdots$	$21-30, \cdots$	$31-40, \cdots$

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

```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

```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

```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);

}
```

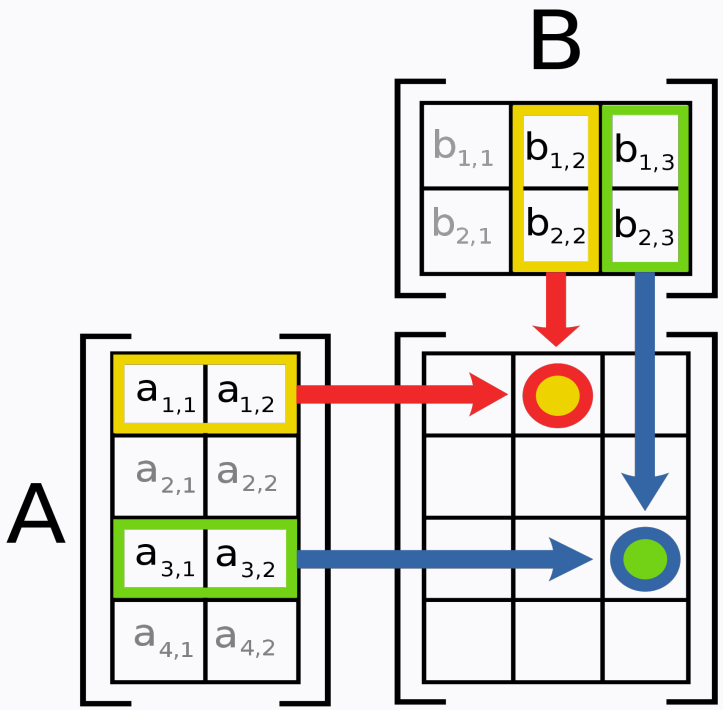
Fortran

```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

```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

```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

```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

```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
         d0
  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))/100
         0d0
  !$omp parallel do private(sum) shared(a,b,c)
  do j = 1, nca
     do k = 1, ncb
        sum = 0d0
        do i = 1, nra
           sum = sum + a(i,j) * b(j,k)
        end do
        c(i,k) = sum
     end do
  end do
  !$omp end parallel do
  call date_and_time(VALUES=value)
  end_time = float(value(6)*60) + float(value(7)) + float(value(8))/1000d
         0

  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 varibale 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.

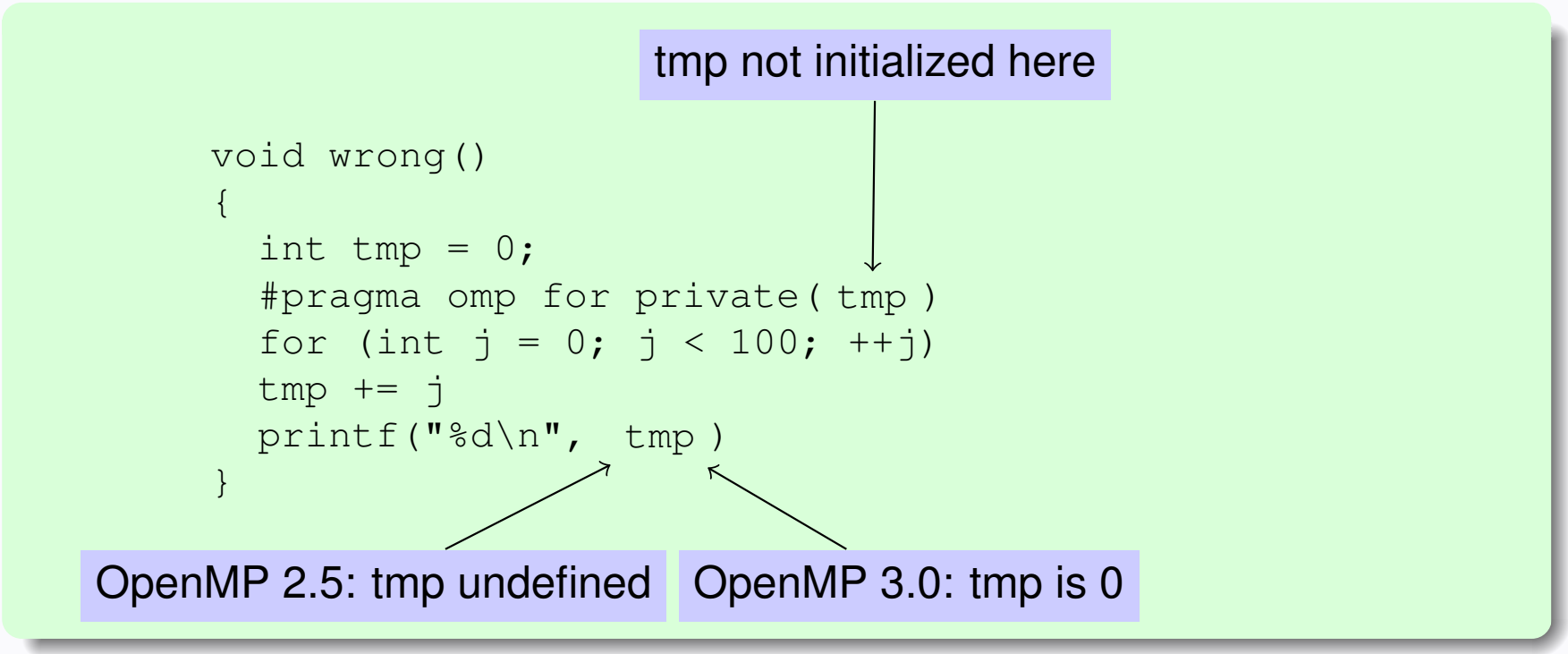
- Critical: Only one thread at a time can enter a `critical` region

```
!$omp parallel do
do i = 1, n
   b = some_function(i)
   !$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



- 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

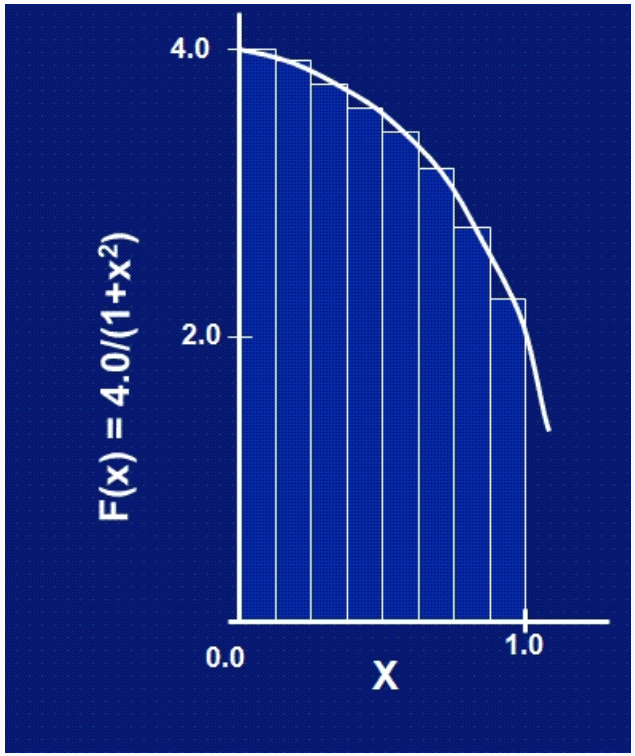
- We know that

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

- So numerically, we can approxiate 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++

```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

```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_omp1.c -o pic_omp
altair:openmp apacheco$ gfortran pi_serial.f90 -o pif
altair:openmp apacheco$ gfortran -fopenmp pi_omp1.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++

```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

```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

```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

```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(VALUES=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(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 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