# OpenMP: a shared-memory parallel programming model

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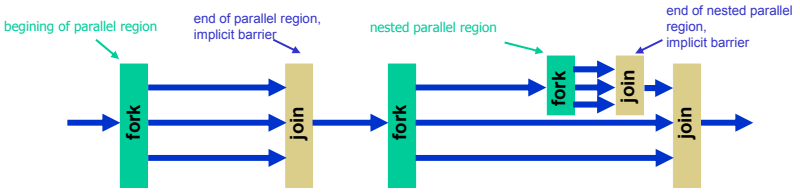
## OpenMP for shared memory

- **First definition in 1996**
  - Today, industry standard, main vendors support it
- **Advantages**
  - Easy to program, debug, modify and maintain
  - Incremental parallelization from the beginning
    - ✓Improve programming productivity
  - Neither communication nor data distribution needed
- **Language extensions to Fortran77/90 and C/C++**
  - Directives or pragmas that can be ignored when compiled in sequential
  - Intrinsic function in OpenMP library
  - Environment variables

## Three components of OpenMP

- **OMP directives/pragmas**
  - These form the major elements of OpenMP programming, they
    - ✓Create threads
    - ✓Share the work amongst threads
    - ✓Synchronize threads
- **Library routines**
  - These routines can be used to control and query the parallel execution environment such as the number of processors that are available for use
- **Environment variables**
  - The execution environment such as the number of threads to be made available to an OMP program can also be set at the operating system level before the program execution is started (an alternative to calling library routines)

## PARALLEL region construct




- **Specification of parallel region**
  - ✓`C$OMP [END] PARALLEL [clause[[,] clause]…]`
  - ✓`#pragma omp parallel [clause [clause]…]`
- **Execution model:**
  - When a thread encounters a parallel region, it creates a team of threads, and it becomes the master of the team. The number of threads in a team remains constant for the duration of the parallel region
  - Parallelism is added incrementally: i.e. the sequential program evolves into a parallel program

## Some useful intrinsic functions

- **To identify individual threads by number**
  - Fortran:

```
INTEGER FUNCTION OMP_GET_THREAD_NUM()
```

  - C/C++:

```
int omp_get_thread_num(void)
```

  - Returns value between 0 … `OMP_GET_NUM_THREADS()-1`

- **To find out how many threads are being used**
  - Fortran:

```
INTEGER FUNCTION OMP_GET_NUM_THREADS()
```

  - C/C++:

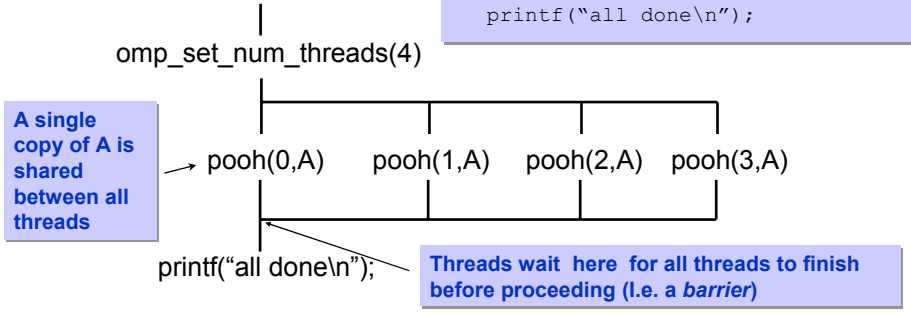
```
int omp_get_num_threads(void);
```

  - Returns value 1 if outside the parallel region else the number of threads available

## PARALLEL region construct

- **Each thread executes the same code redundantly**

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
   int ID = omp_get_thread_num();
   pooh(ID, A);
}
printf("all done\n");
```

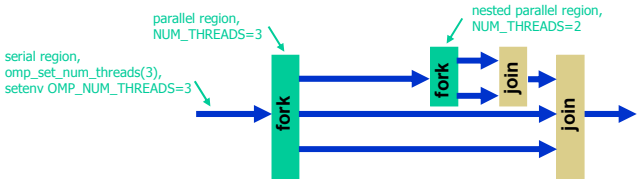


## PARALLEL region construct

- **Clauses:**

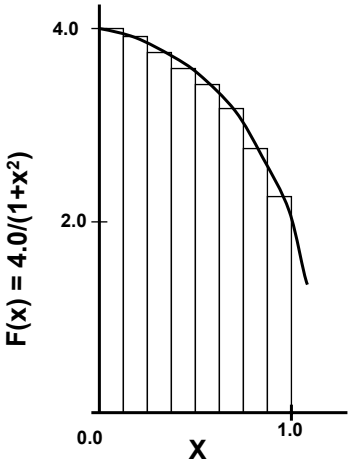
```
NUM_THREADS(integer_exp), IF(logical_exp),
PRIVATE(list), SHARED(list), FIRSTPRIVATE(list),
REDUCTION({operator|intrinsic}:list), COPYIN(list)
```

- **Number of threads at each level:**
  - Environment variable OMP_NUM_THREADS
  - Intrinsic function `omp_set_num_threads` (in serial part)
  - NUM_THREADS clause






## First example: computation of PI




Mathematically, we know that:

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

We can approximate the integral as a sum of rectangles:

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

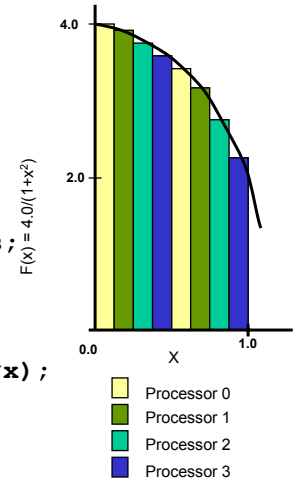
Where each rectangle has width $\Delta x$ and height $F(x_i)$ at the middle of interval i.

# First example: computation of PI

```
static long num_steps = 100000;
double step;
void main ()
{
        int i;
        double x, pi, sum = 0.0;

        step = 1.0/(double) num_steps;

        for (i=1;i<= num_steps; i++){
              x = (i-0.5)*step;
              sum = sum + 4.0/(1.0+x*x);
              }
        pi = step * sum;
}
```

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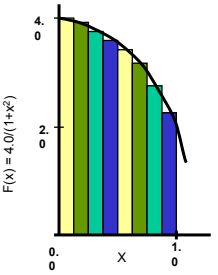
# First example: computation of PI

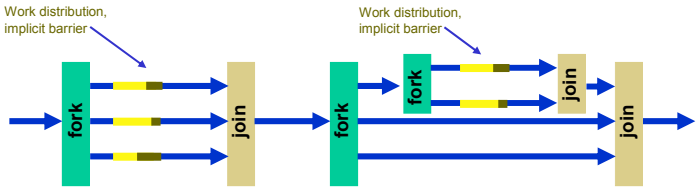
```
#include <omp.h>
static long num_steps = 100000;
double step;
#define NUM_THREADS 2

void main ()
{       int i, id;
        double x, pi, sum;

        step = 1.0/(double) num_steps;
        omp_set_num_threads(NUM_THREADS)
#pragma omp parallel private(x, i, id) reduction(+:sum)
{
        id = omp_get_thread_num();
        for (i=id+1; i<=num_steps; i=i+NUM_THREADS) {
                x = (i-0.5)*step;
                sum = sum + 4.0/(1.0+x*x);
                }
}
        pi = sum * step;
}
```



# Work distribution




- **Work sharing constructs**
  - Split up loop iterations among the threads in the team
  - Give a different structured block to each thread in the team
  - Give a structured block to just one thread in the team



# Work distribution: DO loops

- **Syntax:**
  - ✓ `#pragma for [clause[clause]…]`
  - ✓ `C$OMP [END] DO [clause[[,] clause]…]`
- **Clauses:**
  - Data scope: **`PRIVATE(list), LASTPRIVATE(list), FIRSTPRIVATE(list), REDUCTION(list)`**
  - Iteration scheduling: **`SCHEDULE(type[,chunk])`**
  - Synchronization: **`NOWAIT, ORDERED`**

## First example: computation of PI

```
#include <omp.h>
static long num_steps = 100000;
double step;
#define NUM_THREADS 2
void main ()
{
      int i;
      double x, pi, sum = 0.0;

      step = 1.0/(double) num_steps;
      omp_set_num_threads(NUM_THREADS)
#pragma omp parallel for reduction(+:sum) private(x)
      for (i=1; i<=num_steps; i++){
            x = (i-0.5)*step;
            sum = sum + 4.0/(1.0+x*x);
      }
      pi = step * sum;
}
```



## Loop scheduling strategies

- **Loop schedules:**
  - **SCHEDULE(STATIC[,chunk])**: iterations are divided into pieces of a size specified by `chunk`. Pieces are statically assigned to threads in a round-robin fashion following thread number.
  - **SCHEDULE(DYNAMIC[,chunk])**: iterations are broken into pieces of size specified by `chunk`. Pieces are dynamically assigned to threads.
  - **SCHEDULE(GUIDED[,chunk])**: the chunk size is reduced in an exponentially decreasing manner with each dispatched piece of the iteration space. `chunk` specifies the minimum size.

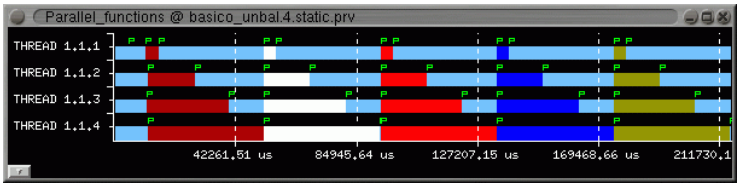
# Synthetic example: work unbalance

```
      PROGRAM test
      PARAMETER (N=1024)
      REAL dummy(N), factor
      INTEGER i, iter, time

      factor=1/1.0000001

      DO iter=1,5
C$OMP PARALLEL DO SCHEDULE(STATIC)
C$OMP&          SHARED(dummy) PRIVATE(i, time)
         DO i=0,N
            dummy(i)= dummy(i)*factor
            time = i/100
            call delay(time)
         ENDDO
      ENDDO

      END
```

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# Synthetic example: work unbalance

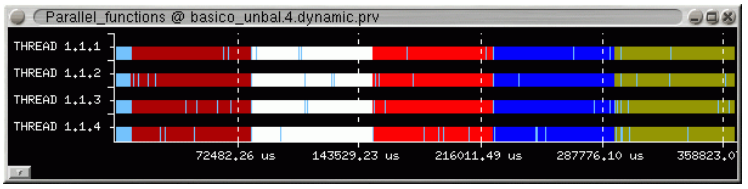
```
      PROGRAM test
      PARAMETER (N=1024)
      REAL dummy(N), factor
      INTEGER i, iter, time

      factor=1/1.0000001

      DO iter=1,5
C$OMP PARALLEL DO SCHEDULE(DYNAMIC)
C$OMP&          SHARED(dummy) PRIVATE(i, time)
         DO i=0,N
            dummy(i)= dummy(i)*factor
            time = i/100
            call delay(time)
         ENDDO
      ENDDO

      END
```

- **Low unbalance**



# Synthetic example: work unbalance

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      PROGRAM test
      PARAMETER (N=1024)
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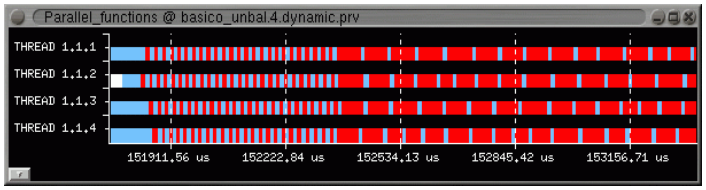
         DO i=0,N
            dummy(i)= dummy(i)*factor
            time = i/100
            call delay(time)
         ENDDO
      ENDDO

      END
```

- **Low unbalance**
- **High overhead**

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# Synthetic example: work unbalance

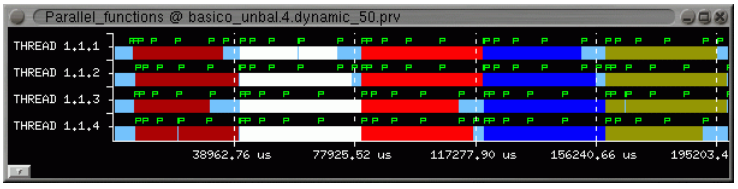
```
      PROGRAM test
      PARAMETER (N=1024)
      REAL dummy(N), factor
      INTEGER i, iter, time

      factor=1/1.0000001

      DO iter=1,5
C$OMP PARALLEL DO SCHEDULE(DYNAMIC, 50)
C$OMP&          SHARED(dummy) PRIVATE(i, time)
         DO i=0,N
            dummy(i)= dummy(i)*factor
            time = i/100
            call delay(time)
         ENDDO
      ENDDO

      END
```

- **Less overhead**
- **Some imbalance:**
  - Heavy chunks towards the end



# Synthetic example: work unbalance

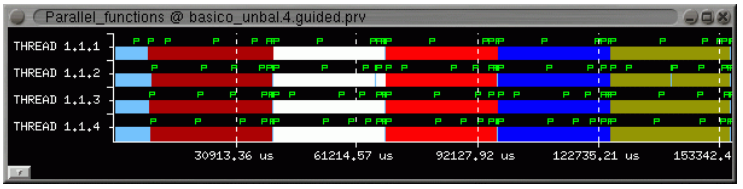
```
      PROGRAM test
      PARAMETER (N=1024)
      REAL dummy(N), factor
      INTEGER i, iter, time

      factor=1/1.0000001

      DO iter=1,5
C$OMP PARALLEL DO SCHEDULE(GUIDED)
C$OMP&          SHARED(dummy) PRIVATE(i, time)
         DO i=0,N
            dummy(i)= dummy(i)*factor
            time = i/100
            call delay(time)
         ENDDO
      ENDDO

      END
```

- **Less overhead**
- **Good load balance:**
  - Heavy chunks towards the beginning
- **Dynamic:**
  - Non repetitive pattern

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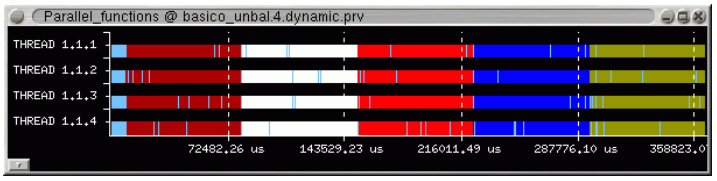
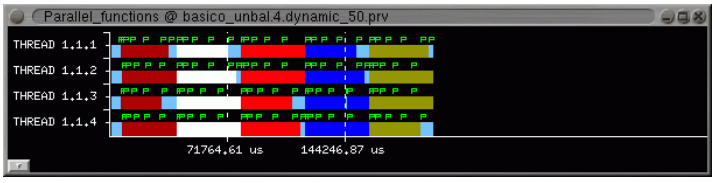
# Synthetic example: work unbalance

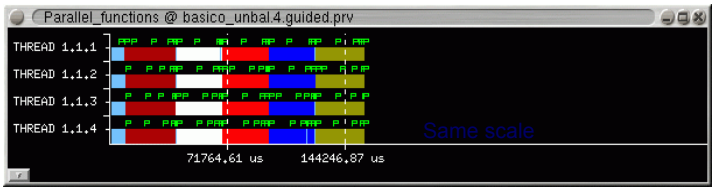
- **Dynamic**




- **Dynamic,50**




- **Guided**



## Work distribution: SECTIONS

- **SECTIONS: worksharing construct that gives a different structured block to each thread in a team**
- **Fortran:**

```
$OMP SECTIONS [clause [[,] clause] …]
  :
$OMP SECTION
  :
$OMP END SECTIONS [clause]
```

- **C/C++:**

```
#pragma omp sections [clause [clause] …]
{
#pragma omp section
     [structured-block]
#pragma omp section
    [structured-block]
:
}
```

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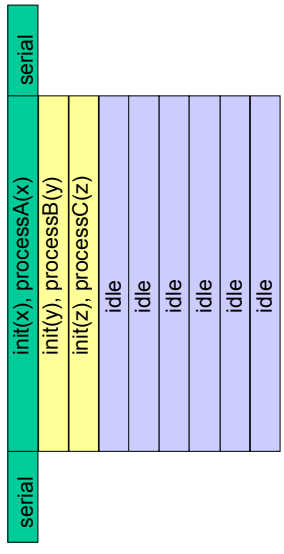
## Work distribution: SECTIONS

- **Example**

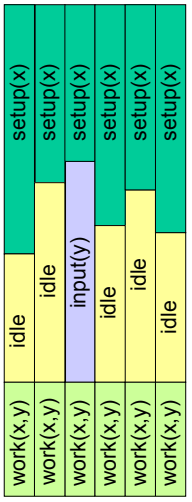
```
!$OMP PARALLEL
!$OMP SECTIONS
!$OMP SECTION
      call init(x)
      call processA(x)
!$OMP SECTION
      call init(y)
      processB(y)
!$OMP SECTION
      call init(z)
      processC(z)
!$OMP END SECTIONS
!$OMP END PARALLEL
```



## Work distribution: SINGLE

- **SINGLE: worksharing that gives a structured block to a single thread in a team**
- **Example**

```
#pragma omp parallel
{
   setup(x);
#pragma omp single
{
   input(y);
}
work(x,y);
}
```

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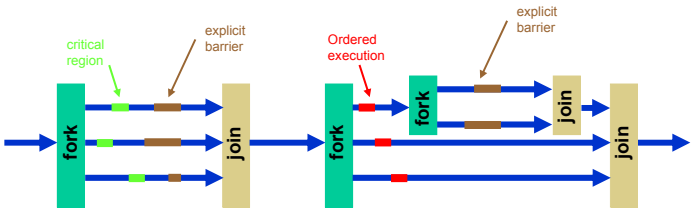
## How do threads interact?

- **OpenMP is a shared memory model**
  - ✓ Threads communicate by sharing variables
- **Unintended sharing of data causes race conditions**
  - ✓ Race condition: when the program's outcome changes as the threads are scheduled differently
- **To control race conditions**
  - ✓ Use synchronization to protect data conflicts
- **Synchronization is expensive so**
  - ✓ Change how data is accessed to minimize the need for synchronization

## OpenMP synchronization constructs




- **Mutual exclusion:**
  `C$OMP [END] CRITICAL [(name)]` `#pragma critical [(name)]`
- **Atomic execution:**
  `C$OMP ATOMIC` `#pragma atomic`
- **Barrier synchronization:**
  `C$OMP BARRIER` `#pragma barrier`
- **Ordered execution for loops:**
  `C$OMP [END] ORDERED` `#pragma ordered`

## Synchronization: CRITICAL sections

- **Only one thread at a time can enter a critical section**

```
float res;
#pragma omp parallel
{      float B;    int i;
#pragma omp for
       for(i=0;i<niters;i++){
            B =  big_job(i);
#pragma omp critical
            consum (B, RES);
       }
}
```

Threads wait their turn – only one at a time calls consum

## Synchronization: ATOMIC access

- Atomic is a special case of a critical section that can be used for certain simple statements
- It applies only to the access to a memory location (the read and update of X in the following example)

```
C$OMP PARALLEL PRIVATE(B)
      B =  DOIT(I)
C$OMP ATOMIC
      X = X + B

C$OMP END PARALLEL
```

- Makes use of special instructions in the processor

## Synchronization: BARRIER

- Each thread waits until all threads arrive

```
#pragma omp parallel shared (A, B, C) private(id)
{
      id=omp_get_thread_num();
      A[id] = big_calc1(id);
#pragma omp barrier
#pragma omp for
      for(i=0;i<N;i++) C[i]=big_calc3(i,A);
#pragma omp for nowait
      for(i=0;i<N;i++) B[i]=big_calc2(C,i);
      A[id] = big_calc3(id);
}
```

implicit barrier at the end of a for worksharing

No implicit barrier due to nowait

Implicit barrier at the end of parallel region

## Synchronization: ORDERED execution

- The ordered construct enforces the sequential order for a block (in the example, following the lexicographical iteration ordering)

```
#pragma omp parallel private (tmp)
#pragma omp for ordered
      for (I=0;I<N;I++){
            tmp = NEAT_STUFF(I);
#pragma ordered
            res += consum(tmp);
      }
```

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## Memory consistency: FLUSH

- The flush construct denotes a sequence point where a thread tries to create a consistent view of memory
  - All memory operations (both reads and writes) defined prior to the sequence point must complete
  - All memory operations (both reads and writes) defined after the sequence point must follow the flush
  - Variables in registers or write buffers must be updated in memory
- Arguments to flush specify which variables are flushed
  - No arguments specifies that all thread visible variables are flushed.

## Memory consistency: FLUSH

- This example shows how FLUSH is used to implement pair-wise synchronization

```
      integer ISYNC(NUM_THREADS)
C$OMP PARALLEL DEFAULT (PRIVATE) SHARED (ISYNC)
      IAM = OMP_GET_THREAD_NUM()
      ISYNC(IAM) = 0
C$OMP BARRIER
      CALL WORK()
      ISYNC(IAM) = 1      ! I'm all done; signal this to others
C$OMP FLUSH(ISYNC)
      DO WHILE (ISYNC(NEIGH) .EQ. 0)
C$OMP FLUSH(ISYNC)
      END DO
C$OMP END PARALLEL
```

Make sure other threads can see my write

Make sure the read picks up the latest copy from memory



## Dynamic work generation schemes

```
while(p != NULL){
  do_work(p->data);
  p = p->next;
}
```

Worksharing

```
int n=0, i=0;
NODEPTR q=p;
NODEPTR *r;
while(q != NULL){
  n++;
  q = q->next;
}
r=allocate(n *
       sizeof(NODEPTR));
while(p != NULL){
  r[i++]=p;
  p = p->next;
}
#pragma omp parallel for
for (i=0; i<n; i++)
  do_work(r[i]->data);
free(r);
```

- OpenMP has survived with no support for this kind of parallelization strategies until now (version 2.5)

## Dynamic work generation schemes

```
while(p != NULL){
  do_work(p->data);
  p = p->next;
}
```

Worksharing

```
int n=0, i=0;
NODEPTR q=p;
NODEPTR *r;
while(q != NULL){
  n++;
  q = q->next;
}
r=allocate(n *
       sizeof(NODEPTR));
while(p != NULL){
  r[i++]=p;
  p = p->next;
}
#pragma omp parallel for
for (i=0; i<n; i++)
  do_work(r[i]->data);
free(r);
```

Workqueuing

```
#pragma intel omp parallel taskq
{
  while(p != NULL){
    #pragma intel omp task
      do_work(p->data);
    p = p->next;
  }
}
```

- **Decouples work generation and execution**
  - One thread generates all work
  - Amount of work unknown

Intel extension to 2.0



## Another example: handling recursivity

```
        ...
C$OMP SINGLE
        CALL traverse(1, list, next)
C$OMP END SINGLE
        ...

        SUBROUTINE traverse(i, list, next)
        INTEGER i, list(100), next(100)
        INTEGER res
C$OMP TASK
       CALL compute(list, list(i), res)
C$OMP CRITICAL
       total = total + res
C$OMP END CRITICAL
C$OMP END TASK
        IF (next(i) .NE. 0) THEN
                CALL traverse(next(i), list, next)
        END IF
        END
```

OpenMP extension in 3.0