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OpenMP Fundamentals
Fork-join model and data environment

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Agenda: OpenMP Fundamentals

OpenMP brief introduction

- overview, a bit of history, main components, execution model, memory model, language syntax

The fork-join model

- creating parallel regions: the parallel construct
- manually distributing work among threads
- sequential code inside the parallel region: the master construct

Data environment

- data-sharing attributes: private and shared data
- data races when sharing variables and critical sections
- data-sharing rules, default attributes in the data environment

OpenMP overview

Parallel Programming Model

- (initially) Designed for shared memory parallel computers
  - » single address space across the host memory system
- But now it also includes multi-device architectures (GPUs, Accelerators,…)
  - » it may imply additional (per device) address spaces
  - » support of data mapping from/to each address space

Maintained by the Architecture Review Board (ARB)

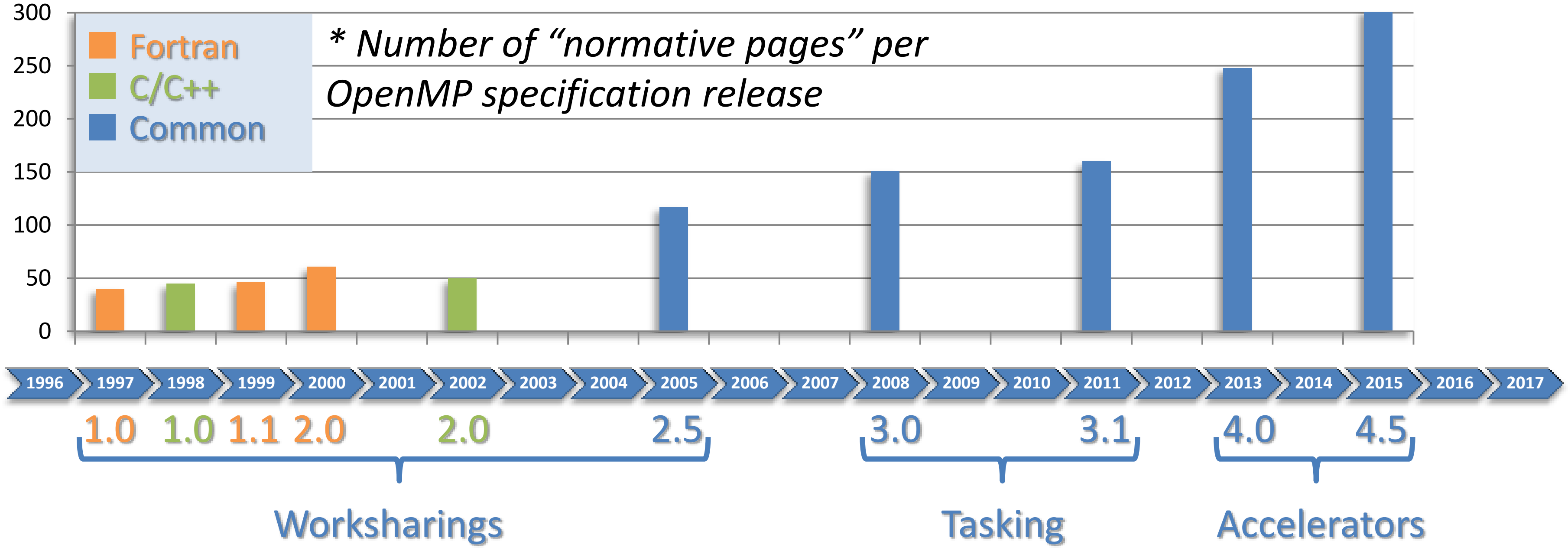
- Permanents members: AMD, ARM, Cray, Fujitsu, HP, IBM, Intel, Micron, NEC, NVIDIA, Oracle, Red Hat and Texas Instruments
- Auxiliary members: ANL, LLNL, BSC, cOMPunity, EPCC, LANL, LBNL, NASA, ORNL, RWTH Aachen University, SNL, TACC and UH

Supported by most compiler vendors

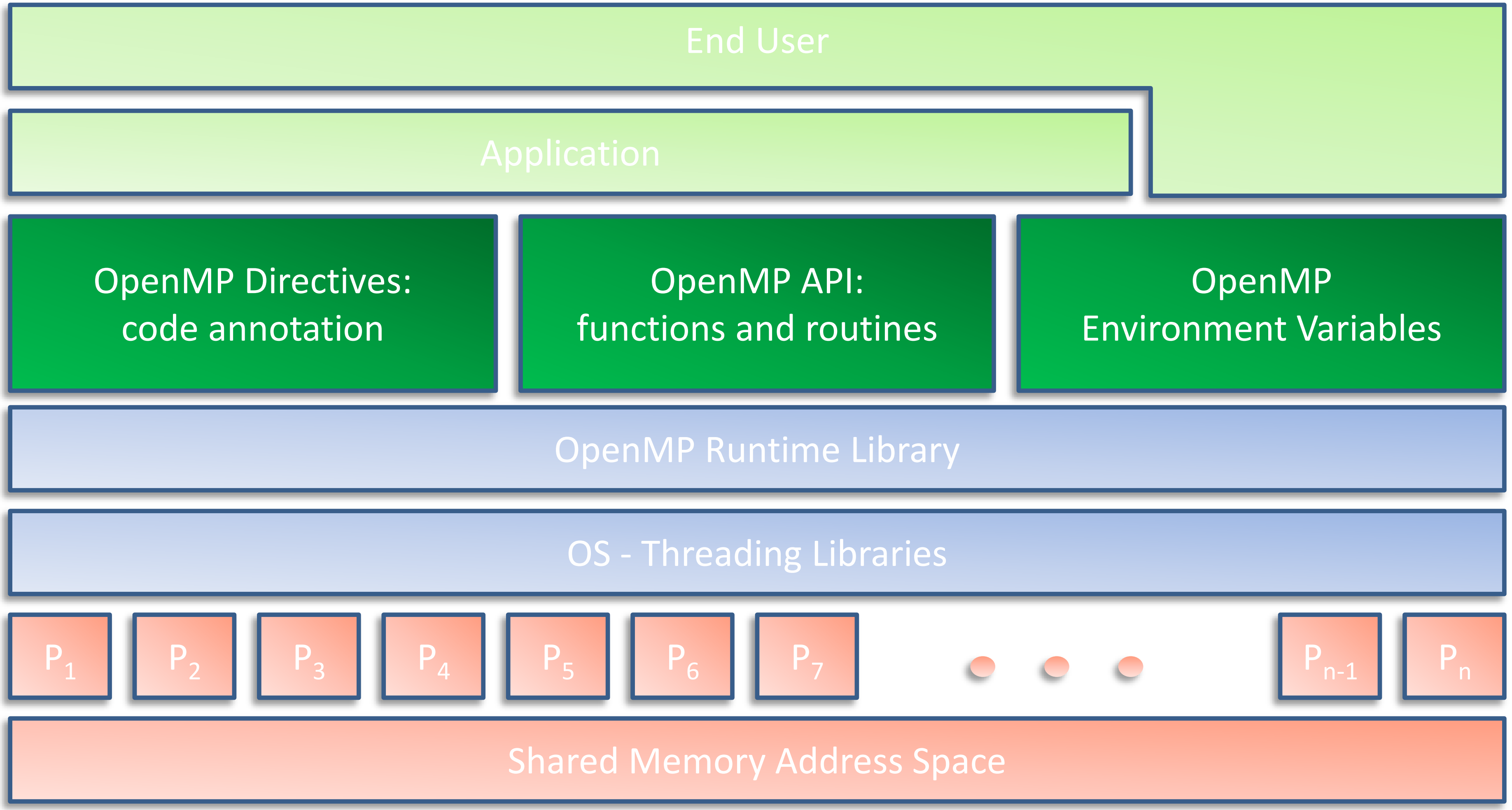
- Intel, IBM, PGI, TI, Sun, Cray, Fujitsu, MS, HP, GCC,…

History of the OpenMP specification

A mature parallel programming model (more than 20 years old)
Complex to face the whole (latest) specification



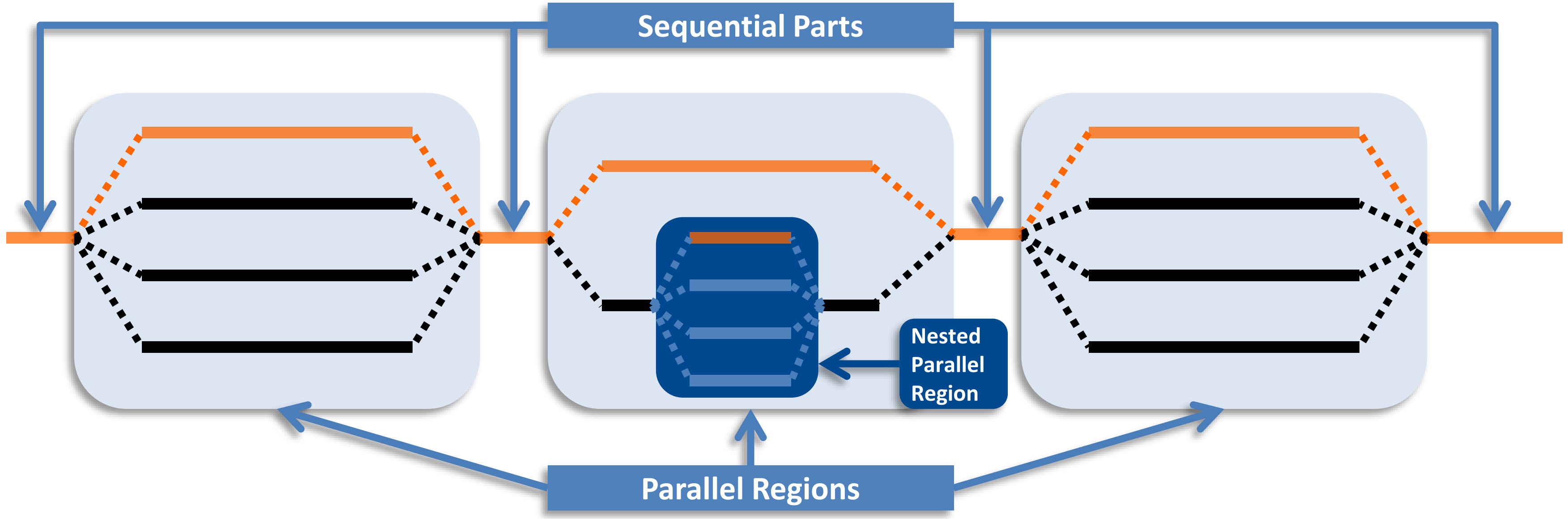
OpenMP components


End User
Application
OpenMP Directives: code annotation
OpenMP API: functions and routines
OpenMP Environment Variables
OpenMP Runtime Library
OS - Threading Libraries
P_1
P_2
P_3
P_4
P_5
P_6
P_7
P_{n-1}
P_n
Shared Memory Address Space

Execution model

Based on the fork-join paradigm

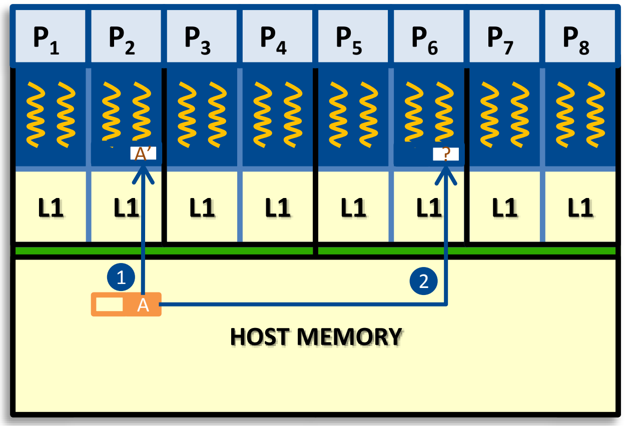
- a thread team is a set of threads which co-operate on a task
- the **master thread** is responsible for coordinating the team
- usually running one thread per processor (but could be more / or less)
- different threads may follow different control flows



Memory model

A relaxed-consistency memory model

- different threads may see different values for the same (shared) variable → not consistent
- consistency is only guaranteed at specific points
  - » explicit points: the flush directive
  - » implicit points: other directives
- luckily, the implicit points are usually enough



The operation enforcing consistency is called the flush operation

- all previous read and writes by this thread have been completed
- all these changes are visible to all other threads
- they are also known as *fences* or *memory barriers*
- In the example: At moment (1) P2 has read the variable A from memory and it has modified it, then at moment (2) P6 wants to read variable A.

OpenMP (directive) syntax

In Fortran language

– through a specially formatted comment

```
sentinel directive-name [clause[[,] clause]...]
```

– where sentinel is one of
  - » !$OMP or C$OMP or *$OMP in fixed format
  - » !$OMP in free format

– API runtime services
  - » omp_lib module contains the subroutine and function definitions

In C/C++ language

– using compiler directives*

```
#pragma omp directive-name [clause[[,] clause]...]
```

– API runtime services
  - » omp.h contains the API prototypes and data types definitions

** directives are ignored if compiler does not recognize OpenMP*

The structured block

Most directives apply to a structured block:

```
#pragma omp directive-name [clause[[,] clause]...]
structured-block
```

- block of one or more statements with one entry point / one exit point
  - » i.e. branching in or out is not allowed
  - » terminating the program is allowed (abort/exit)

```
#pragma omp directive-name clause1(…) clause2(…)
{
  set_of_instructions (no  branch in/out);
}
```
✓

```
#pragma omp directive-name clause1(…) clause2(…)
for (int i = 0;  i < SIZE; i++) {
    A [ i ] = 0;
}
```
✓

```
#pragma omp directive-name clause1(…) clause2(…)
{
  set_of_instructions;
  if ( expr ) exit(0);
}
```
✓

```
#pragma omp directive-name clause1(…) clause2(…)
for (int i = 0;  i < SIZE; i++) {
    A [ i ] = 0;
    if ( i == INDEX ) break;
}
```
✗

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The Fork-Join Model

Parallel programming with OpenMP

The parallel construct

Creating a parallel region

– always attached to a structured block

```
#pragma omp parallel [clause[[,] clause]...]
{structured-block}
```

Where clause:

– num_threads (expression)
– if (expression)
– shared (var-list)
– private (var-list)
– firstprivate (var-list)
– default (dtype)
– reduction (var-list)

Specifying the number of threads

The maximum number of threads is controlled by

– an internal control variable (ICV) called nthreads-var
  - » the OpenMP API nthreads-var setter

```
void omp_set_num_threads (int value);   // subsequent parallel region
```

  - » the OpenMP API nthreads-var getters

```
int omp_get_num_threads (void);   // current team number of threads
int omp_get_max_threads (void);   // maximum number of threads
```

  - » the OpenMP environment variable nthreads-var setter

```
$ export OMP_NUM_THREADS=<list>
$ ./myProgram
```

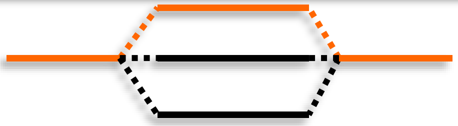
– the num_threads clause (overriding nthreads-var value)

Example: creating a parallel region (1)

Creating a parallel region of 3 threads (num_threads clause)

```
#include <stdio.h>

void main (void)
{
  #pragma omp parallel num_threads(3)
  {
    printf("Hello world!\n");
  }
}
```

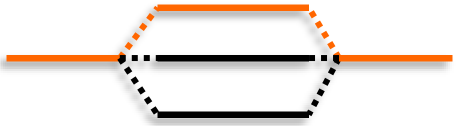
```
$ gcc -fopenmp myHello.c -o myHello
$ ./myHello
Hello world!
Hello world!
Hello world!
```



Creating a parallel region of 3 threads (omp_set_num_threads)

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

void main (void)
{
  omp_set_num_threads(3);
  #pragma omp parallel
  {
    printf("Hello world!\n");
  }
}
```

```
$ gcc -fopenmp myHello.c -o myHello
$ ./myHello
Hello world!
Hello world!
Hello world!
```

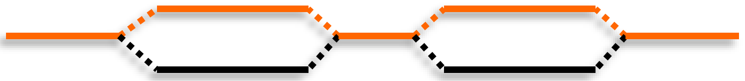


Example: creating a parallel region (3)

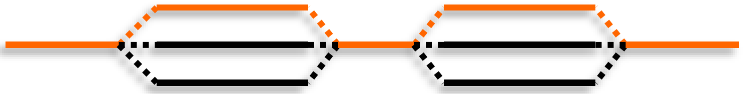
But still more useful is to use the environment variable

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

void main (void)
{

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

  #pragma omp parallel
  {
    printf("...and godbye!\n");
  }

}
```

```
$ gcc -fopenmp myHello.c -o myHello
$ OMP_NUM_THREADS=2 ./myHello
Hello world...
Hello world...
...and goodbye!
...and goodbye!
```



```
$ OMP_NUM_THREADS=3 ./myHello
Hello world...
Hello world...
Hello world...
...and goodbye!
...and goodbye!
...and goodbye!
```

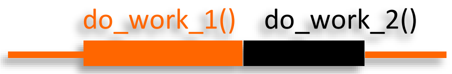


Replicate work inside the parallel region

When two "blocks of code" may run in parallel…

```
#include <stdio.h>

void main (void)
{
  do_work_1();
  do_work_2();
}
```

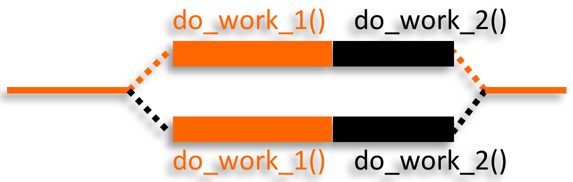
```
$ time ./myProgram
real    0m4.003s
user    0m0.000s
sys     0m0.000s
```



… we just include them within a parallel region (replicate)

```
#include <stdio.h>
#include <omp.h>
void main (void)
{
  #pragma omp parallel num_threads(2)
  {
    do_work_1();
    do_work_2();
  }
}
```

```
$ time ./myProgram
real    0m4.104s
user    0m0.000s
sys     0m0.000s
```



Identifying threads inside the parallel region

Inside a parallel region each thread has its own identifier

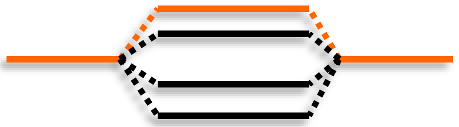
```
int omp_get_thread_num (void);   // get the identification number for the current thread/team
```

- from 0 to N-1 (where N is the number of threads of the team)
- master thread is always identified by 0 (zero)
- routine returns 0 (zero) if called outside a parallel region

Example using the thread identifier

```
#include <stdio.h>
#include <omp.h>
void main (void)
{
  #pragma omp parallel num_threads(4)
  {
    int id = omp_get_thread_num();
    printf("Hello world! I am the thread %d.\n“, id);
  }
}
```

```
$ ./myThreadId
Hello world! I am the thread 2.
Hello world! I am the thread 1.
Hello world! I am the thread 0.
Hello world! I am the thread 3.
```

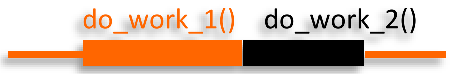


Distribute work inside the parallel region (1)

When two “blocks of code” may run in parallel…

```c
#include <stdio.h>

void main (void)
{
  do_work_1();
  do_work_2();
}
```

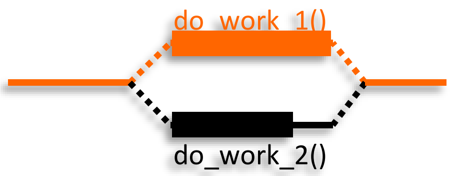
```
$ time ./myProgram
real    0m4.003s
user    0m0.000s
sys     0m0.000s
```



… we can use the thread identifier to distribute work

```c
#include <stdio.h>
#include <omp.h>
void main (void)
{
  #pragma omp parallel num_threads(2)
  {
    int id = omp_get_thread_num();
    if ( id == 0 ) do_work_1();
    if ( id == 1 ) do_work_2();
  }
}
```

```
$ time ./myProgram
real    0m2.604s
user    0m0.000s
sys     0m0.000s
```



Distribute work inside the parallel region (2)

Thread identifier must be carefully used

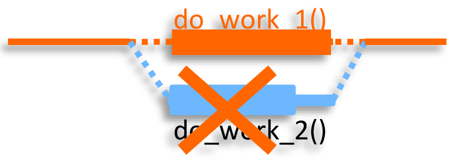
– Rely on the number of threads is never a good idea

– OpenMP offers other mechanisms to distribute work

The following example is actually wrong

```c
#include <stdio.h>
#include <omp.h>
void main (void)
{
  #pragma omp parallel
  {
    int id = omp_get_thread_num();
    if ( id == 0 ) do_work_1();
    if ( id == 1 ) do_work_2();
  }
}
```

```
$ export OMP_NUM_THREADS=1
$ time ./myProgram
real    0m2.604s
user    0m0.000s
sys     0m0.000s
```

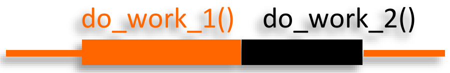


Distribute work inside the parallel region (3)

Workaround to the unassigned work problem

```
#pragma omp parallel
{
  int id = omp_get_thread_num();
  if ( id == 0 ) do_work_1();
  if ( id == 1  || omp_get_num_threads() < 2) do_work_2();
}
```

```
$ export OMP_NUM_THREADS=1
$ time ./myProgram
real    0m4.003s
user    0m0.000s
sys     0m0.000s
```



But still non-optimal solution

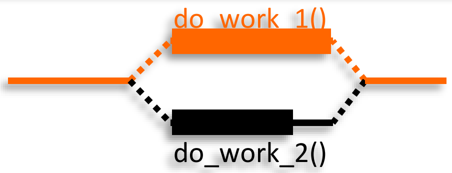
– Think on more than 2 sections?

WARNING!!!

Don't try this at home*

** But you can use it during this tutorial*

```
$ export OMP_NUM_THREADS=2
$ time ./myProgram
real    0m2.604s
user    0m0.000s
sys     0m0.000s
```

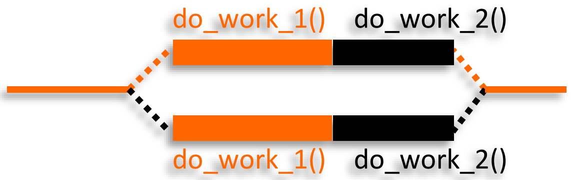


Summary: replicate vs distribute work

Replicate work (all threads execute the same work)

```c
#include <stdio.h>
#include <omp.h>
void main (void) {
  #pragma omp parallel num_threads(2)
  {
    do_work_1();
    do_work_2();
  }
}
```

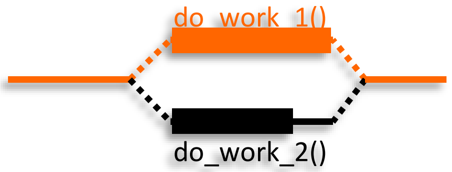
```
$ time ./myProgram
real    0m2.604s
user    0m0.000s
sys     0m0.000s
```



Distribute work (threads “share” the amount of work)

```c
#include <stdio.h>
#include <omp.h>
void main (void) {
  #pragma omp parallel num_threads(2)
  {
    int id = omp_get_thread_num();
    if ( id == 0 ) do_work_1();
    if ( id == 1 ) do_work_2();
  }
}
```

```
$ time ./myProgram
real    0m2.604s
user    0m0.000s
sys     0m0.000s
```



Distribute loop iterations inside the parallel region

Target: independent loop

```
#define SIZE 1204
double A[SIZE];
void main (void)
{
    for (int i = 0;  i < SIZE; i++) {
     A [ i ] = 0;
    }
}
```

— Programmer must guarantee no dependences across loop iterations

— Compute lower bound and upper bound for each thread (using actual boundaries, thread id and number of threads)

Parallel approach

```
#include <omp.h>
#define SIZE 1204
double A[SIZE];
void main (void)
{
  #pragma omp parallel
  {
    int id = omp_get_thread_num();
    int nt = omp_get_num_threads();
    int lb = id * (SIZE/nt);
    int ub = (id+1)*(SIZE/nt) + ( (id==nt-1)? (SIZE%nt) : 0 );
    for (int i = lb; i < ub; i++) {
     A [ i ] = 0;
    }
  }
}
```

— But still non-optimal solution
  » more threads than iterations
  » load imbalance (iters/threads)

Parallel construct: the if clause

Avoids creating parallel regions

```
#pragma omp parallel if(expr)
{structured-block}
```

- sometimes we only want to run in parallel under certain conditions
- if expr evaluates to false parallel construct will only use 1 thread
- still creates a new team and data environment

Example of the if-clause usage

```
#include <omp.h>
#define SIZE ...
double A[SIZE];
void main (void)
{
  #pragma omp parallel if(SIZE>256)
  {
    int id = omp_get_thread_num();
    int nt = omp_get_num_threads();
    int lb = id*(SIZE/nt);
    int ub = (id+1)*(SIZE/nt)+((id==nt-1)?(SIZE%nt):0);
    for (int i = lb; i < ub; i++) {
     A [ i ] = 0;
    }
  }
}
```

Master construct

Only the master thread executes a given region

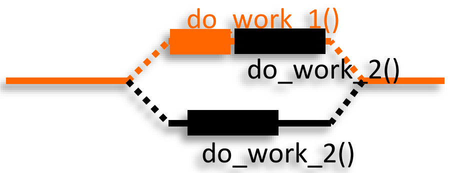
```
#pragma omp master
{structured-block}
```

- the master construct has no clauses

Master construct's semantics

- other threads do not execute the structured block
- there is no implicit barrier at the entry
- there is no implicit barrier at the end

```
#pragma omp parallel num_threads(2)
{
  int id = omp_get_thread_num();
  #pragma omp master
  do_work_1(); // execute with one thread
  do_work_2(id); // execute with N threads
}
```



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Data Environment

Parallel programming with OpenMP

OpenMP constructs and data environment

Scoping variables in an OpenMP construct (ownership)

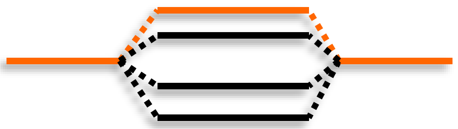
- determine the scope for each variable: shared and private
- shared data can be accessed by all the threads
- private data can only be accessed by the owner thread

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

double PI = 3.14159265359;

void main (void)
{
  int id = 0;
  #pragma omp parallel num_threads(4) shared(PI) private(id)
  {
    id = omp_get_thread_num();
    printf("Hello world! I am thread %d. I like %f.\n", id, PI);
  }
}
```

```
$ ./myProgram
Hello world! I am thread 2. I like 3.141593.
Hello world! I am thread 0. I like 3.141593.
Hello world! I am thread 1. I like 3.141593.
Hello world! I am thread 3. I like 3.141593.
```



Privatizing variables inside the construct

The variable inside the construct is a new variable

- the new variables have the same type than original variable
- in parallel construct it means all threads have a different variable
- they can be accessed without any kind of synchronization

The private (storage) and firstprivate (storage + copy) clauses

```
#pragma omp parallel {private|firstprivate}(list)
{structured-block}
```

- private variables have undefined value when starting the block
- firstprivate variables are initialized to the value of the original one

```
double PI = 3.14159265359;

#pragma omp parallel private(PI)
{
   PI = <expr>;
   ...
}
printf("PI = %f \n", PI);
```

```
double PI = 3.14159265359;

#pragma omp parallel firstprivate(PI)
{
     <lvalue> = f(PI); // including PI = f(PI);
     ...
}
printf("PI = %f \n", PI);
```

The threadprivate directive

Allows to create a per-thread copy of “global” variables

```
#pragma omp threadprivate(var-list)
```

threadprivate can be applied to:
- global or static variables
- class static data members (C++)

The threadprivate storage persist
- but persistence is complex

```
#include <stdio.h>
char buffer[SIZE];
#pragma omp threadprivate(buffer)

void main (void)
{
  #pragma omp parallel
  {
    buffer = <expr>;
    . . .
  }
}
```

Now buffer have a per-thread copy (~private)

Using *static* variable:

```
#include <stdio.h>

char* foo(void)
{
  static char buffer[SIZE];
  #pragma omp threadprivate(buffer)
  . . .
  return buffer;
}

void main (void)
{
  #pragma omp parallel
  {
    char *a = foo();
    . . .
  }
}
```

Now foo() can be called by multiple threads at the same time

Returns correct address to caller

Sharing variables inside the parallel region (1)

The variable is “the same” outside/inside the construct

- in parallel construct it means all threads see the same variable (address)
- but not necessarily the same value (consistency issue)
- usually need some kind of synchronization to update them correctly
  - » synchronization: mutual exclusion or atomic updates
  - » synchronization also guarantees consistency points

```c
#include <stdio.h>

double PI = 3.14159265359;

void main (void)
{
  int id = 0;
  #pragma omp parallel num_threads(4) shared(PI)
  {
    PI = 3;
  }
  printf("PI = %f \n", PI);
}
```

- all threads read same variable
- after the parallel region variable modifications still are visible

```
$ ./myProgram
PI = 3.000000;
```

Sharing variables inside the parallel region (2)

Modifying shared variables ('a' and 'b') inside the parallel region

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

int a = 0, b = 0 , ITERS = 100;
void main (void)
{
  int NT = 4; // Number of threads
  #pragma omp parallel num_threads(NT) shared(a, b, NT, ITERS)
  {
    #pragma omp master
    a = NT*ITERS;

    for (int i = 0; i<ITERS; i++) {
      b = b + 1;
    }
  }
  assert ( a == NT*ITERS, "Value of 'a' is incorrect!!!")  // correct
  assert ( b == NT*ITERS, "Value of 'b' is incorrect!!!")  // incorrect
}
```

- variables 'NT' & 'ITERS' have no data race
- variable 'a' has no data race
- variable 'b' may give incorrect results
- a bit of assembly… b = b + 1 → load, arithmetic-op(+) and store
- An example of two 'b=b+1' executed concurrently: b=5, ((b+1)+1) → b=7

Reg-1	Thread-1	b	Thread-2	Reg-2
r1=5	load b, r1	5		r1=X
r1=6	increment r1	5		r1=X
r1=6		5	load b, r1	r1=5
r1=6	store r1, b	6		r1=5
r1=6		6	increment r1	r1=6
r1=6		6	store r1, b	r1=6

The critical construct

Mutual exclusion regions

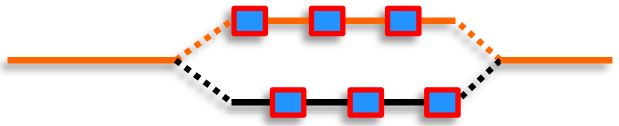
```
#pragma omp critical [(name) [hint(hint-expression)] ]
{structured-block}
```

Critical construct's semantics

– only one thread can be executing the region at any given time
– by default all critical regions are synchronized all-to-all
– if you provide a name only those regions with the same name synchronize

```
#include <omp.h>
void main (void)
{
  int b = 0, NT = 4 , ITERS = 100;

  #pragma omp parallel num_threads(NT) shared(b, ITERS)
  for (int i = 0; i<ITERS; i++) {
    #pragma omp critical
    b = b + 1;
  }
  assert ( b == NT*ITERS, "Value of 'b' is incorrect!!!"); // correct
}
```



– in this example we would get a extremely poor performance:
– almost all the code has been serialized!!!
– … but this is a well-know pattern

The reduction pattern and the manual approach

All threads are accumulating values into a single variable

problem

```
#include <omp.h>
void main (void) {
  int b = 0, NT = 2;
  omp_set_num_threads(NT);
  #pragma omp parallel shared(b, NT)
  {
    for (int i = 0; i<ITERS; i++) {
      b = b + 1;
    }
  }
  assert ( b == NT*ITERS, "Value of 'b' is incorrect!!!")
}
```

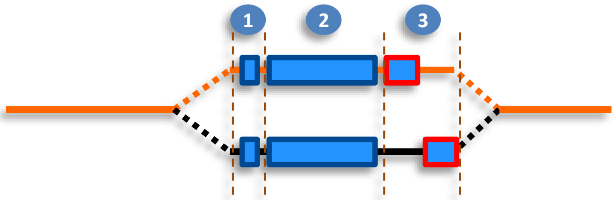
Data Race!!!

solution

```
#include <omp.h>
void main (void)
{
  int b = 0, NT = 2;
  omp_set_num_threads(NT);
  #pragma omp parallel shared(b, NT)
  {
1   int p_b = 0;
    for (int i = 0; i<ITERS; i++) {
2     p_b = p_b + 1;
    }
    #pragma omp critical
3   b = b + p_b;
  }
  assert ( b == NT*ITERS, "Value of 'b' is incorrect!!!")
}
```

The manual approach:

1. create-initialize a *per-thread* copy
2. accumulate partial results using this private copy (no synchro)
3. accumulate each partial results into the original variable (critical)



Parallel construct and the reduction mechanism

The reduction clause

```
#pragma omp parallel reduction(operator:list)
{structured-block}
```

Applying it to previous example (data-sharing attribute)

```
#include <omp.h>
void main (void)
{
  int b = 0, NT = 2;
  omp_set_num_threads(NT);
  #pragma omp parallel reduction(+:b)
  for (int i = 0; i<ITERS; i++) {
      b = b + 1;
  }
  assert ( b == NT*ITERS, "Value of 'b' is incorrect!!!")
}
```

– the compiler creates a private copy that is properly initialized (identity)
– the compiler ensures that the shared variable is properly (and safely) updated with all partial results
– valid operators are: `+, -, *, |, ||, &, &&, ^, min, max`
– but we can also specify user-defined reductions

This doesn't mean that all data races are solved with reduction!!!

Data environment: what is the default?

Pre-determined data-sharing attributes

- threadprivate variables are threadprivate
- dynamic storage duration objects are shared (malloc, new,…)
- static data members are shared
- variables declared inside the construct
  - » static storage duration variables are shared
  - » automatic storage duration variables are private
- the loop iteration variable(s)…

Explicit data-sharing clauses (shared, private, firstprivate,…)

- If default clause present, what the clause says
  - » none means that the compiler will issue an error if the attribute is not explicitly set by the programmer (very useful!!!)

Implicit data-sharing rules, depends on the construct

- For the parallel region the default is shared

Default data-sharing attributes (in practice)

Data-sharing attribute for each variable referenced in parallel?

```
int a ;
void foo ( int b ) {
  int c;
  #pragma omp parallel
  {
    int d ;
    a = <expr>;
    b = <expr>;
    c = <expr>;
    d = <expr>;
  }
}
```

– default(none) may help when you are not sure of understand the default

Summary: OpenMP fundamentals

OpenMP constructs: parallel, master and critical

- fork-join model: the **parallel region** → team of threads
- how to **replicate** and (manually) **distribute** work among threads

```
#pragma omp parallel
{
  do_work_1();
  do_work_2();
}
```

```
#pragma omp parallel
{
  int id = omp_get_thread_num();
  if ( id == 0 ) do_work_1();
  if ( id == 1 || NT < 2) do_work_2();
}
```

```
#pragma omp parallel
  {
    int id = < expr >, nt = < expr >;
    int lb = id * (SIZE/nt);
    int ub = (id+1)*(SIZE/nt) + ( (id==nt-1)? (SIZE%nt) : 0 );
    for (int i = lb; i < ub; i++) A [ i ] = 0;
}
```

- restrictions inside the parallel region: **master** and **critical** constructs

The data environment: data sharing clauses

- scoping variables inside a construct: **private** and **shared**
- data sharing attribute **rules**: pre-determined, explicit and implicit determined
- the **data race** problem: no controlled access on shared variables
- using **reduction** variables: partial results reduced into original variable

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Thank you!

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