An introduction to OpenMP

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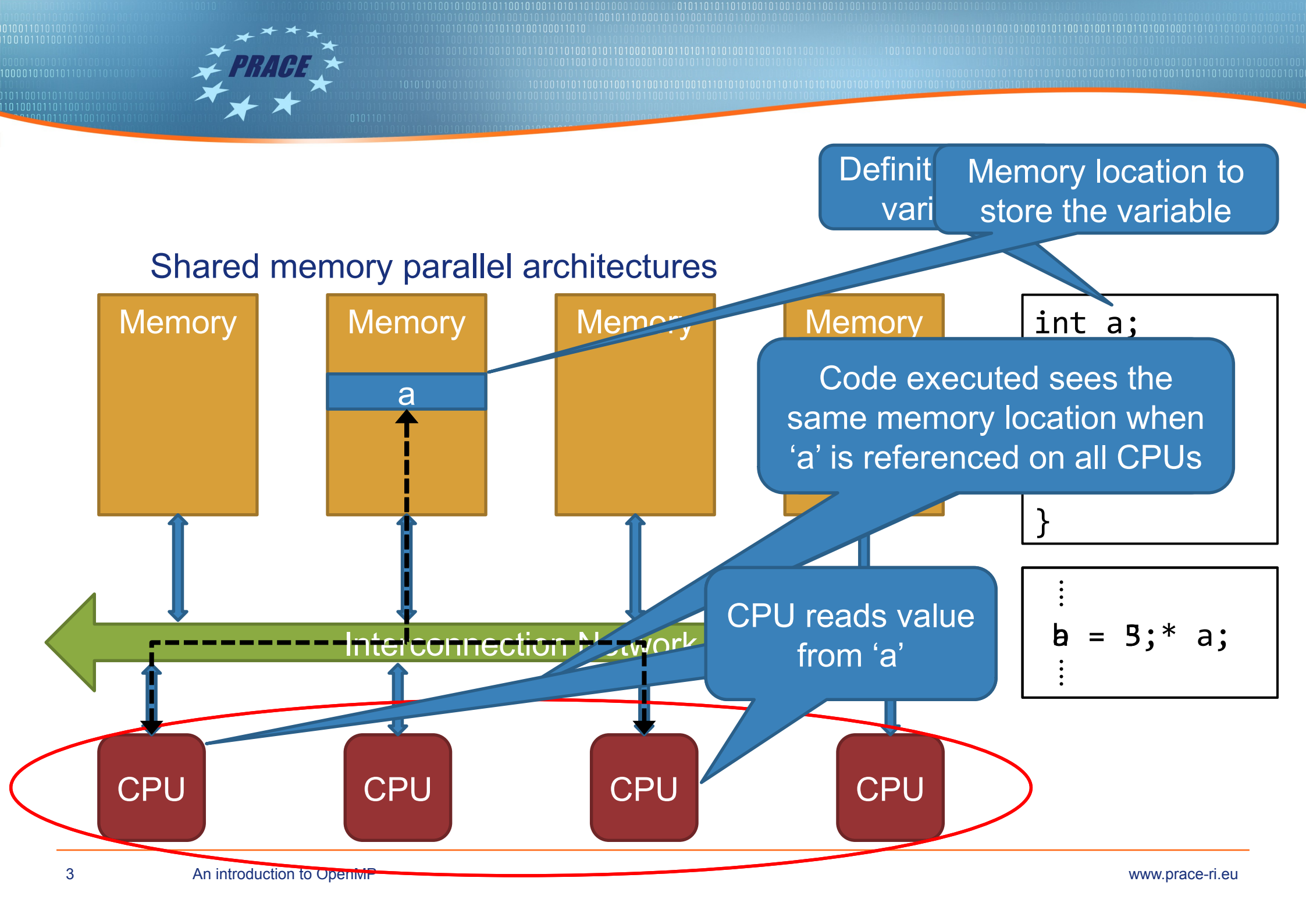
Classification of parallel architectures

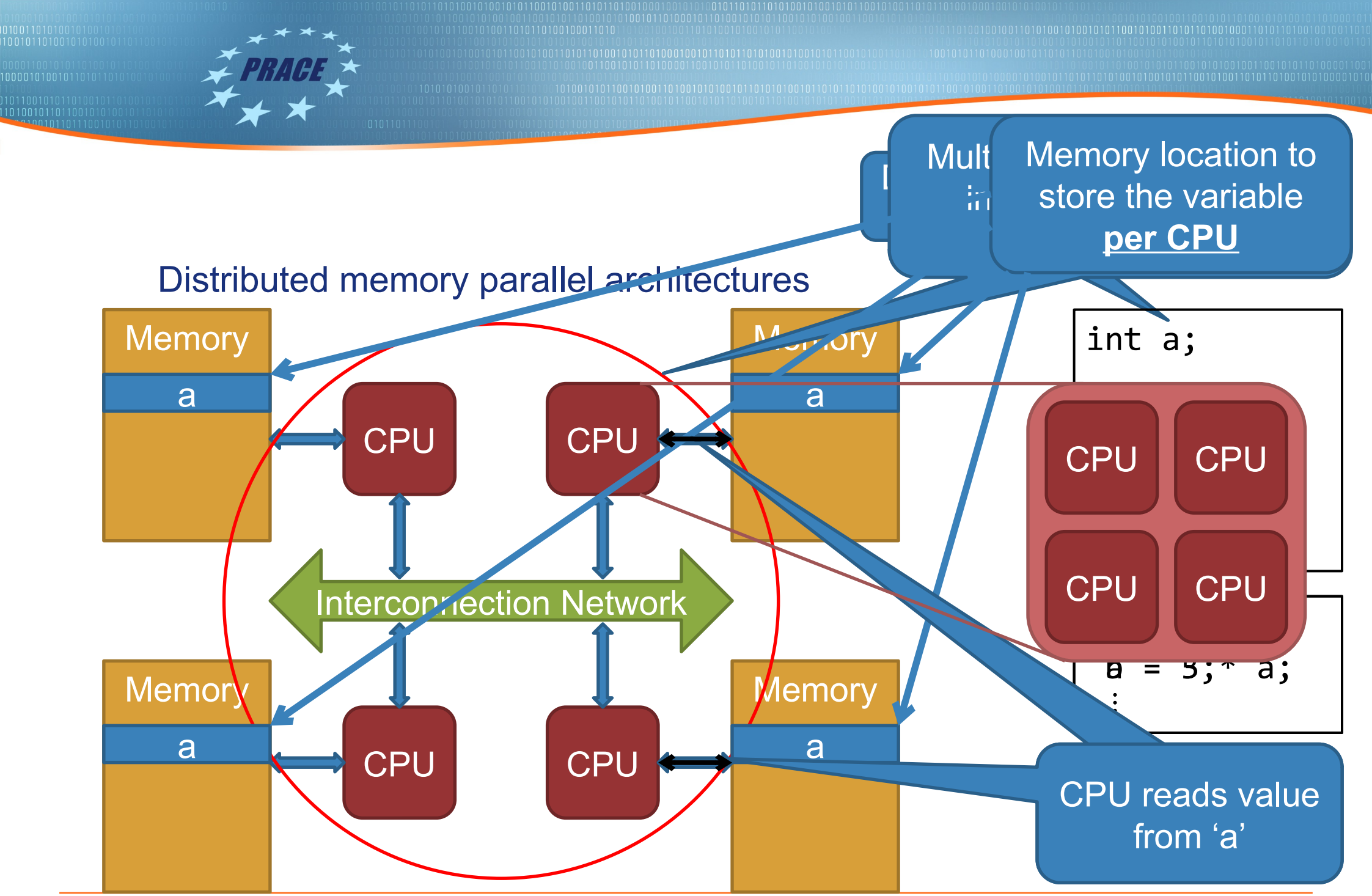
There are many classification schemes for parallel architectures

One of the most useful ones is according to the memory architecture of the system

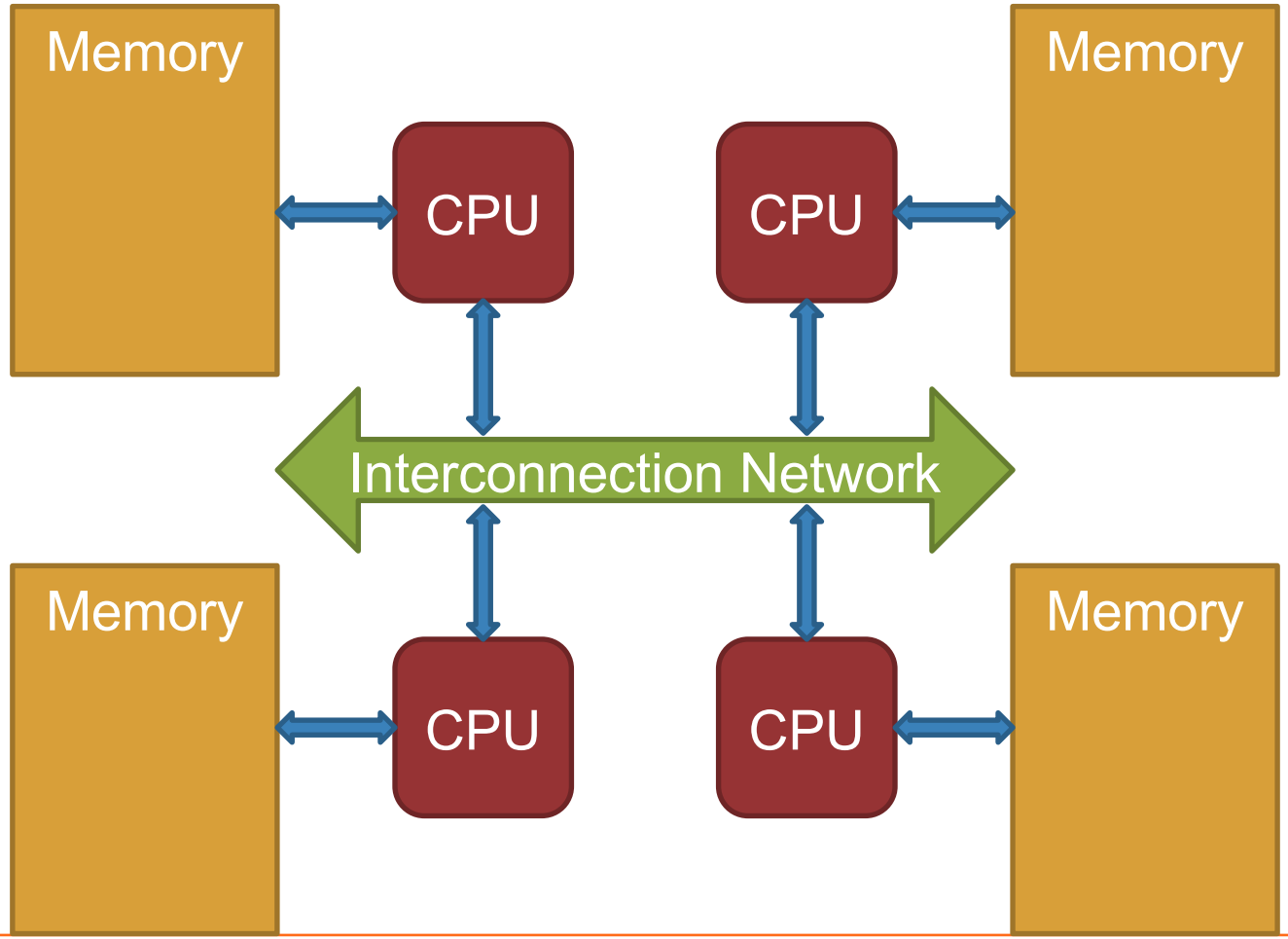
- Shared memory
- Distributed memory
- Distributed shared memory

Largely determines the programming models that can be used to program the specific architecture


Definit
vari
Memory location to store the variable
Shared memory parallel architectures
Memory
Memory
a
Memory
Memory
int a;
}
Code executed sees the same memory location when ‘a’ is referenced on all CPUs
Interconnection Network
CPU reads value from ‘a’
b = 3;* a;
CPU
CPU
CPU
CPU


Distributed memory parallel architectures
Memory location to store the variable per CPU
Memory
a
CPU
CPU
Memory
a
Interconnection Network
Memory
a
CPU
CPU
Memory
a
int a;
CPU
CPU
CPU
CPU
CPU reads value from 'a'

Distributed shared memory parallel architectures



Same organization as distributed memory systems

But memory behaves as in shared memory systems

- Hardware ensures this kind of behavior

Programming models for shared memory parallel architectures

- OpenMP
- Threads
  - POSIX Threads as well as other threading libraries
- Cilk
- Cilk Plus
- Threading Building Blocks
- …

Programming models for distributed memory parallel architectures

MPI

PVM

…

What is the goal when using a parallel programming model?

Problem to be solved is large

- Requires too much time to run on single CPU

Divide input data into smaller chunks

- Smaller size of input ⇒ Faster calculation

Assign every chunk to a CPU

- Using appropriate software abstraction (thread or process)

Every CPU processes its chunk and creates part of the solution

Combine partial solutions into global solution

Threads to express parallelism

- Typically a specific series of steps is followed by the programmer
  - Identification of code that can execute in parallel
  - Put code into separate function
  - Pass (typically) one parameter
    - *An identification number for the thread (ID)*
  - Distribution of workload using the above parameter
    - *Each thread can determine on its own the part of the workload it will process*
    - *How this part of the workload is calculated is usually the same or similar no matter the specific problem being solved*
  - Addition of mutual exclusion/synchronization

The main idea of OpenMP

The steps described in the previous slide:

- Are well defined
- Repeat in many problems

The real problem for the programmer is to find a good way to parallelize the application

- The implementation of the solution can be achieved to an large degree in an automated way

Can the compiler undertake the automated part of programing?

Directive based programming models

There have been several proposals and implementations

- Sequent Fortran
- Cedar Fortran
- PCF Fortran
- SGI
- ANSI X3H5

Most failed because:

- They were not general enough
  - *Could not support enough parallelization approaches of applications*
- They were overlapping
- They were proposed in the wrong point in time

OpenMP

- Why do we need another standard?
  - Previously proposed models were in reality never standardized
    - *Many companies provided their own directives for parallelization*
      - *Similar syntax and meaning*
      - *But different names for the directive*
    - *Created portability issues*
- OpenMP unifies all previous attempts and extends them:
  - A unique set of directives with a uniquely defined syntax and meaning
  - Portability of source code for programming shared memory systems

What is then OpenMP?

It is a specification

- Not a specific implementation

It provides an Application Programming Interface (API) for programming shared memory systems:

- Directives to the compiler
- Run-Time Library
- Environment Variables

It supports C, C++ and Fortran

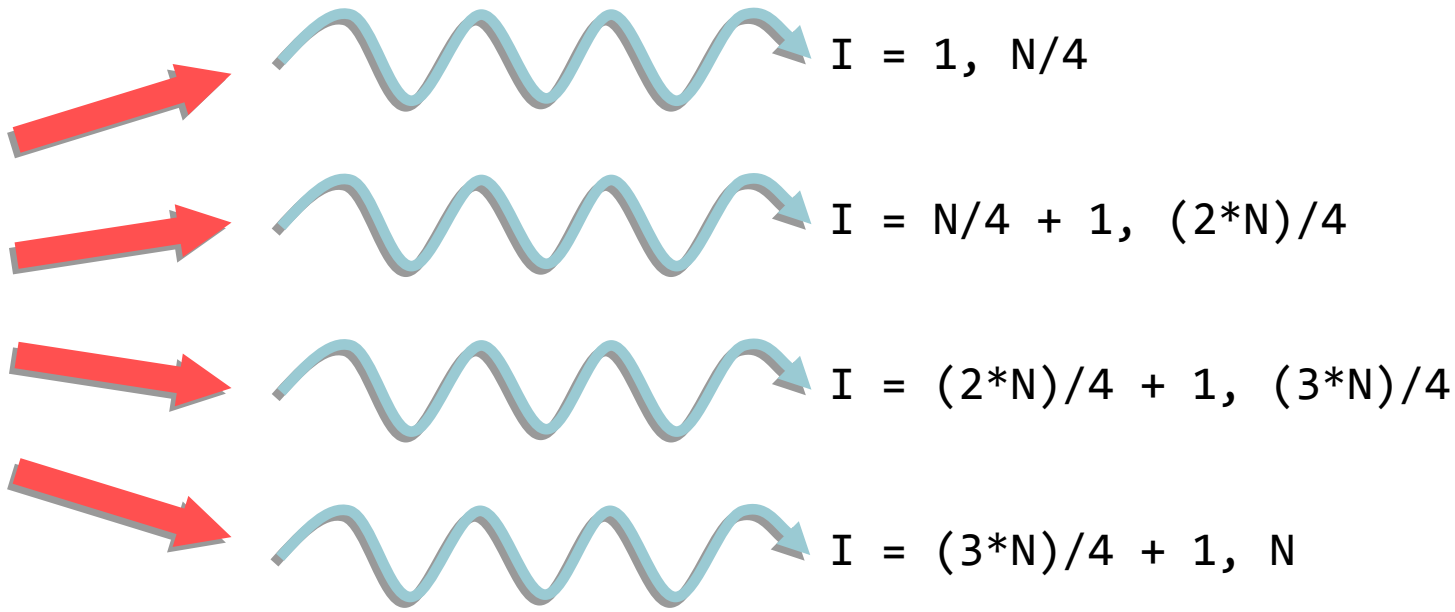
Programs written in OpenMP can also be compiled and run as serial programs

How does OpenMP work?

The programmer directs the compiler where and how it should parallelize code

The compiler creates parallelism

```
$!omp parallel do …
    do 10 I = 1, N
    …
    …
10 continue
```



Who does support OpenMP?

GNU GCC ≥ 4.2

IBM XL Compilers

Sun Microsystems Sun Studio Compilers

Intel Compilers

Portland Group Compilers

Absoft Pro Compilers

Only Fortran

Lahey/Fujitsu Compilers

PathScale Compilers

Microsoft Visual Studio

…

More information about OpenMP

Current specification

OpenMP 5.2, November 2021

Official web site

http://www.openmp.org

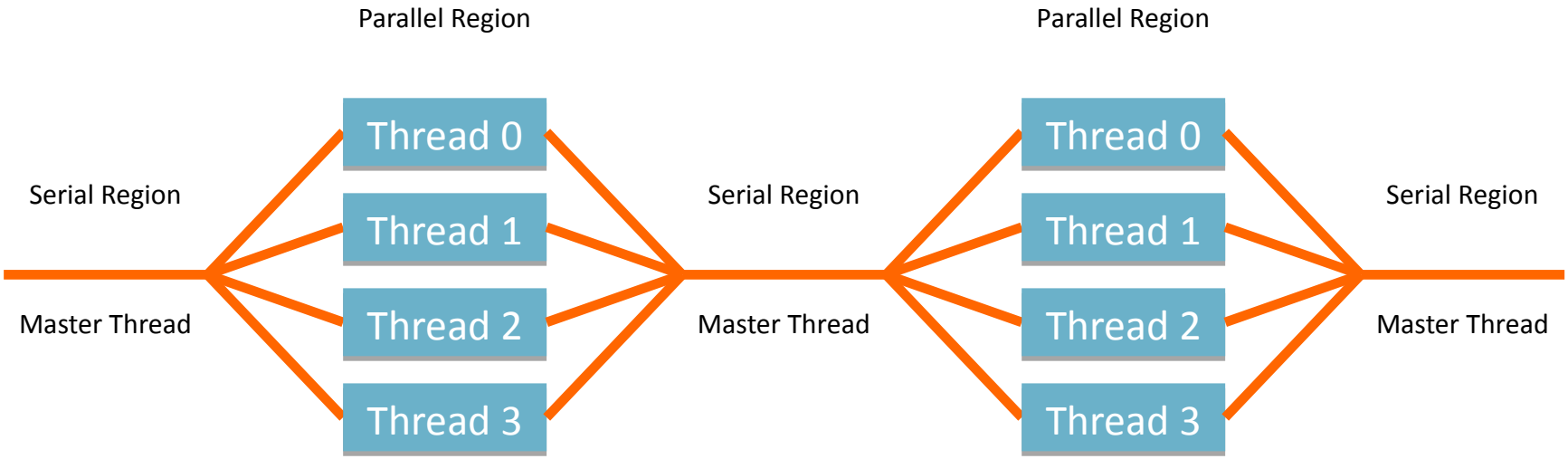
OpenMP user community

http://www.compunity.org

Execution model of OpenMP (1/4)

Based on threads and tasks

Follows the fork-join model



Execution model of OpenMP (2/4)

When a thread encounters a “parallel” directive

- The thread creates a team of threads that includes itself and zero or more additional threads
  - *The thread becomes the “master thread”*
- A set of tasks is created
  - *The code that each task will execute is determined by the code within the “parallel” construct*
- Each task is assigned to a thread and is bound to it
- Execution of the current task is suspended
- Tasks of the newly created team are executed

Execution model of OpenMP (3/4)

- At the end of each parallel region a barrier exists
  - A method to synchronize threads
  - All threads need to reach the barrier
    - *Threads that reach the barrier wait*
    - *As soon as the last thread reaches the barrier, all threads can pass the barrier and continue their execution*
- After the end of a parallel region
  - Only the master thread continues execution

Execution model of OpenMP (4/4)

OpenMP allows optional support for nested parallelism

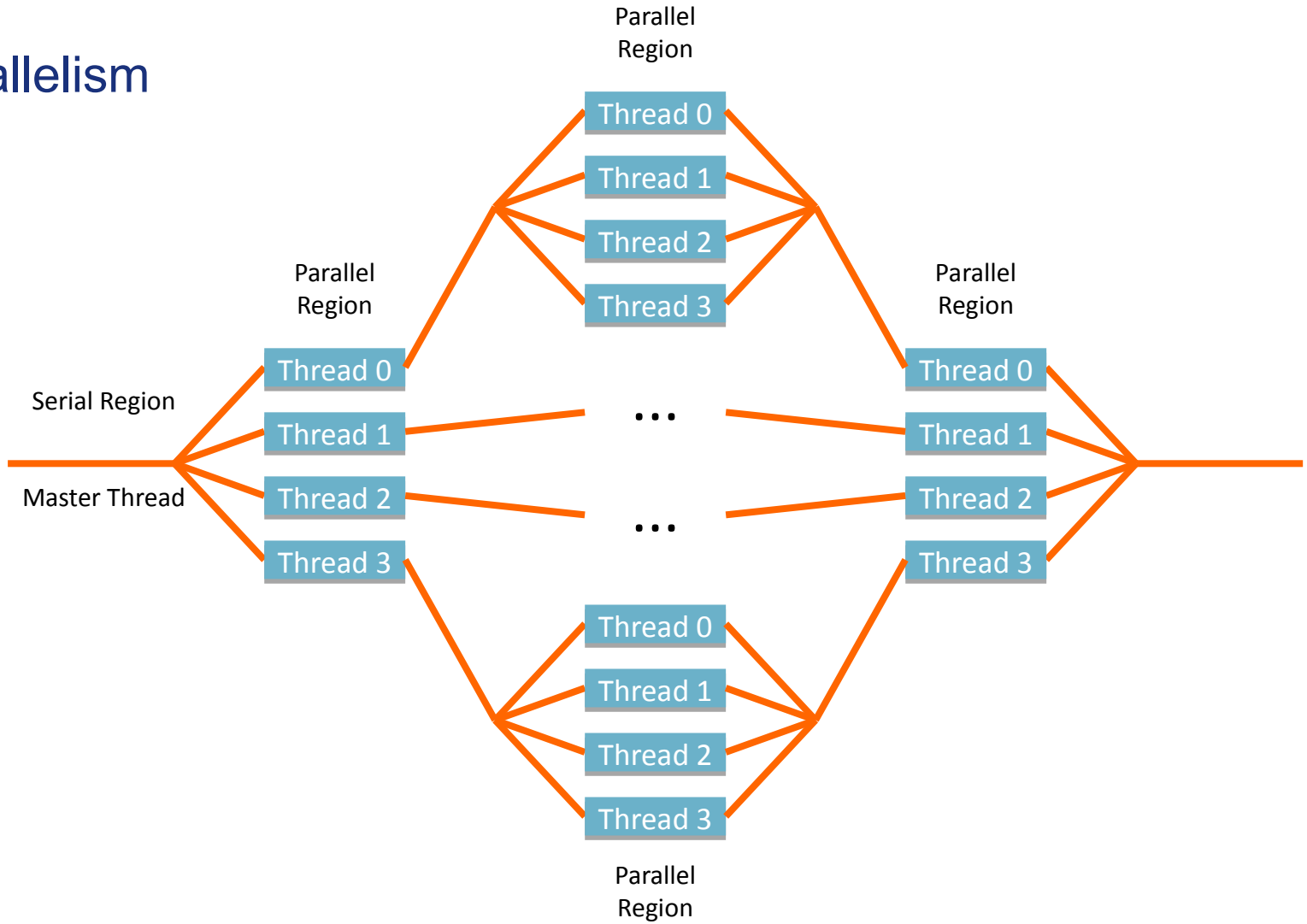
Threads in a parallel region may themselves create new threads

The implementers of OpenMP in a specific compiler decide whether they will support it or not

If not supported every nested parallel construct is ignored

The new team of threads that is created when a parallel construct is encounter is composed only of the encountering thread

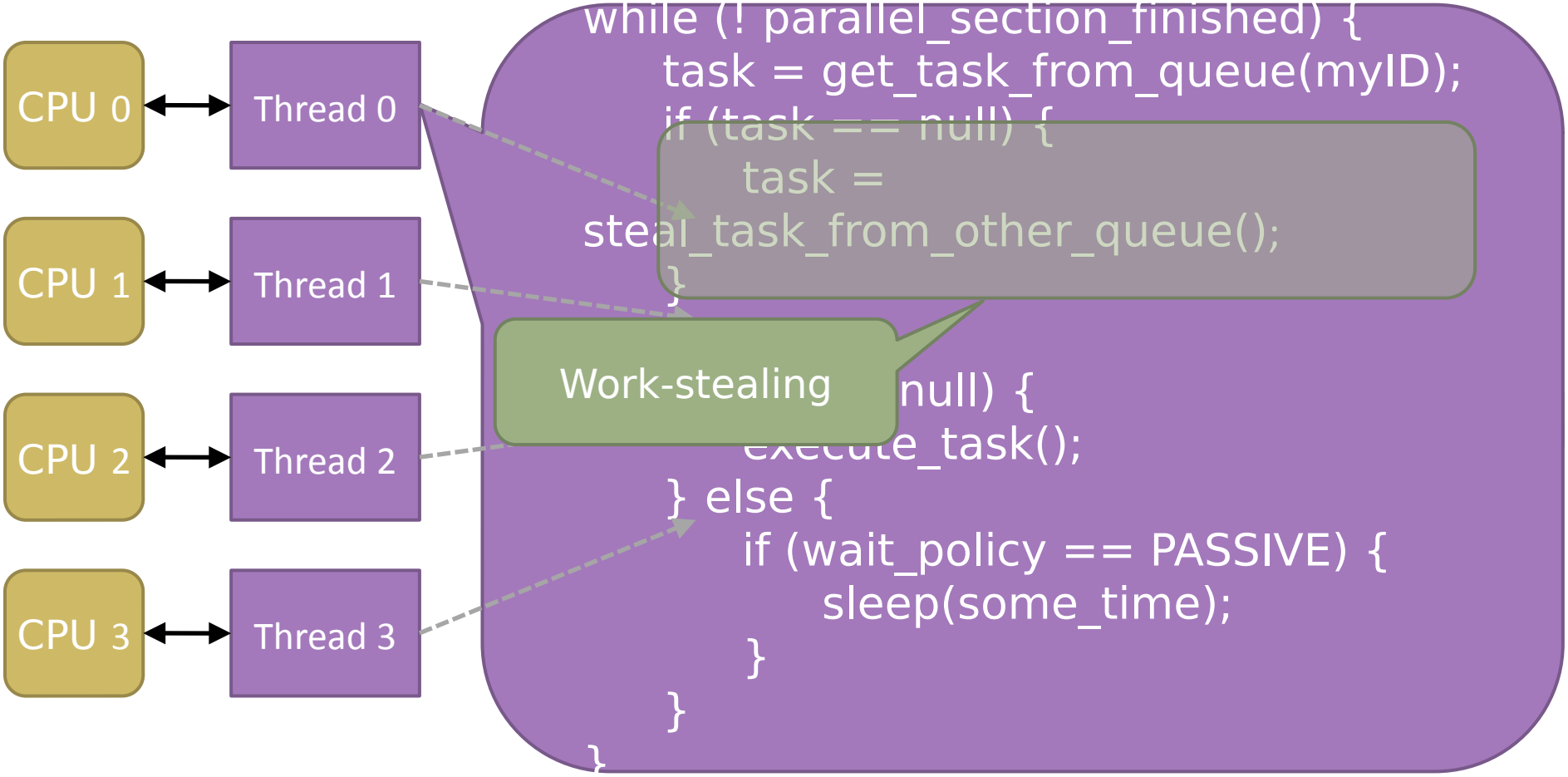
Nested parallelism



Why tasks in addition to threads?

- When a thread is created
  - We determine the code it should execute
  - We define its arguments
  - It constitutes a static way to assign work
- A task only describes the work it should perform
  - How is a task selected to execute?

User-level scheduler



Implementation issues

Many issues mentioned in the previous slide are not required by the OpenMP specification

They depend on the specific implementation

- Will work-stealing be supported or not?
  - *How does it affect performance?*
- What happens with threads when a parallel region ends?
  - *Are they destroyed?*
  - *Are they kept inactive and reused when the next parallel region is encountered?*

As a result, the implementation we discussed is only one possibility among many

- Although it already includes some advanced features

Advantages of tasks

- Tasks are suitable for parallelizing irregular problems
  - Loops with unknown limits
  - Recursive algorithms
  - Producer/Consumer problems
  - Trees
  - Graphs
- The most important addition in version 3.0 of OpenMP

OpenMP directives for C/C++

The “#pragma” mechanism is used

- Directive to the preprocessor

Every OpenMP directive starts with “#pragma omp”

- Directives are case-sensitive

Every OpenMP directive applies to the structured block that immediately follows the directive

General form:

#pragma omp *directive-name [clause [,] clause]…] new-line*

A first example

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

int main(void){
   #pragma omp parallel
   {
   printf( "Hello World from thread %i of %i\n",
     omp_get_thread_num(),
     omp_get_num_threads());
   }
   return 0;
}
```

How many threads?

We didn't define the number of threads to be created

There are 4 ways to do it:

- We add the clause "num_threads(*integer-expression*)" to the "parallel" directive
- The source code calls the function "omp_set_num_threads(*integer-expression*)" from the OpenMP Run-Time Library
  - *Before encountering the "parallel" construct*
- Before executing the application we set the environment variable "OMP_NUM_THREADS" in the shell
- Default number of threads for the specific implementation
  - *Usually the total number of available processors/cores*

Conditional compilation

For OpenMP implementations where a preprocessor is available

- The macro "_OPENMP" is defined
  - *The value of the macro is of the form "yyyymm"*
    - *"yyyy" and "mm": The year and the month when the implemented version of OpenMP was officially accepted*

Useful when functions from the Run-Time Library of OpenMP are called

- If a compiler does not support OpenMP, these functions are not known
  - *Error during the link stage: Undefined reference to `…`*
- What would happen in the previous example if would try to compile it with a compiler that does not support OpenMP?

Example

```
#include <stdio.h>

int main()
{
#ifdef _OPENMP
    printf("Compiled by an OpenMP-compliant implementation.\
n");
#endif

    return 0;
}
```

The “parallel” directive

#pragma omp parallel [clause [[,] clause]…] new-line

structured-block

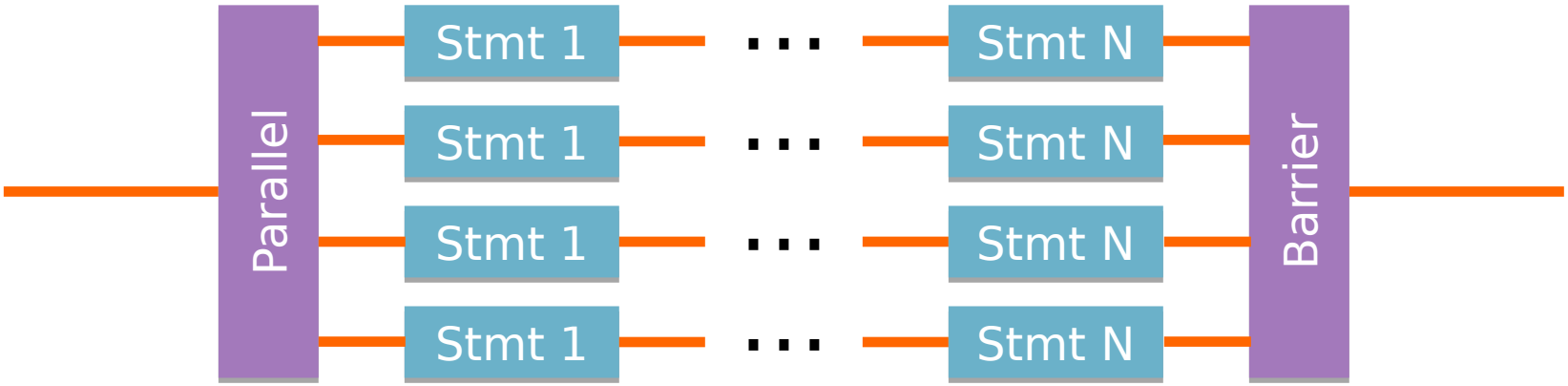
“clause” can be one or more of the following:

- if (scalar-expression)
- num_threads (integer-expression)
- default(shared | none)
- private(list)
- firstprivate(list)
- shared(list)
- copyin(list)
- reduction(operator : list)

Description

The “parallel” construct is the most basic construct in OpenMP

Every thread in the parallel region will execute the “*structured-block*”



Description

"if (*scalar-expression*)"

If the expression is true, the "*structured-block*" will be executed by a group of threads

If the expression is false, the "*structured-block*" will be executed serially

"num_threads (*integer-expression*)"

Defines how many threads will be created to execute the parallel region

Determining the actual number of threads to be used is quite complicated

Depends on a multitude of parameters

OpenMP 4.5 Specification Document, pages 50-51

Description

"default(shared | none)"

"shared": All variables referenced in the "*structured-block*" for which no scope has been explicitly defined will be considered to be shared among threads

"none": The scope for each variable referenced in "*structured-block*" must be specified explicitly

Shared among threads or private per thread

"shared(*list*)"

All variables referenced in "list" become shared among threads

Description

“private(*list*)”

All variables referenced in “list” become private per thread

“firstprivate(*list*)”

All variables referenced in “list” become private per thread

All local copies of the initial variables are initialized with the last value contained in the corresponding variable before encountering the parallel region

Description

"reduction(*operator : list*)"

All variables referenced in "list" become private per thread

All local copies of the initial variables are initialized with an appropriate value (see next slide)

At the end of the parallel region each of the initial variables is updated according to the selected operator and the values of the corresponding local copies

Operators for the “reduction” clause

Operator	Initial value
+	0
*	1
-	0
&	~0
|	0
^	0
&&	1
||	0

Serial addition of vectors (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Serial addition of vectors (2/2)

```
   for (i = 0; i < N; i++) {
        C[i] = A[i] + B[i];
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        printf("%d ", C[i]);
   }

   return(0);
}  /* main() ends here */
```

Addition of vectors with OpenMP (1/3)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Addition of vectors with OpenMP (2/3)

```
#pragma omp parallel
{
   int i, start, end, numOfThreads, numOfElements, id;

   id = omp_get_thread_num();
   numOfThreads = omp_get_num_threads();

   numOfElements = N / numOfThreads;
   start = numOfElements * id;

   if (id != numOfThreads - 1) {
        end = start + numOfElements;
   } else {
        end = N;
   }

   for (i = start; i < end; i++) {
        C[i] = A[i] + B[i];
   }
}  /* #pragma omp parallel ends here */
```

Returns the ID of the thread

Returns the number of threads created in the parallel region

Addition of vectors with OpenMP (3/3)

```
   printf("C = ");
   for (i = 0; i < N; i++) {
        printf("%d ", C[i]);
   }

   return(0);
}  /* main() ends here */
```

Example (Compilation/Execution)

```
$ gcc –O3 –Wall –fopenmp –o my_prog my_prog.c
$ ./my_prog 12
  C = …
$
```

Size of vectors

Variation of vector addition (1/3)

```
int *A, *B, *C;

int main(int argc, char *argv[]) {
   int i, N, start, end, numOfThreads, numOfElements, id;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Variation of vector addition (2/3)

```
#pragma omp parallel shared(N) private(i, id, numOfThreads, numOfElements, start, end)
{
   id = omp_get_thread_num();
   numOfThreads = omp_get_num_threads();

   numOfElements = N / numOfThreads;
   start = numOfElements * id;

   if (id != numOfThreads – 1) {
        end = start + numOfElements;
   } else {
        end = N;
   }

   for (i = start; i < end; i++) {
        C[i] = A[i] + B[i];
   }
}  /* #pragma omp parallel ends here */
```

Variation of vector addition (3/3)

```
   printf("C = ");
   for (i = 0; i < N; i++) {
        printf("%d ", C[i]);
   }

   return(0);
}  /* main() ends here */
```

Why would we prefer the second version?

- Think how you typically write a serial program
  - All variables declared at the beginning of a function
  - No one would really create a new block of code using curly braces to declare the variables inside that block
- OpenMP is designed to easily extend serial programs

Serial addition of matrices (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * N * sizeof(int));
   B = (int *)malloc(N * N * sizeof(int));
   C = (int *)malloc(N * N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Serial addition of matrices (2/2)

```
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             C[i * N + j] = A[i * N + j] + B[i * N + j];
        }
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             printf("%d ", C[i * N + j]);
        }
        printf("\n");
   }

   return(0);
}  /* main() ends here */
```

Addition of matrices using OpenMP (1/3)

```
int *A, *B, *C;

int main(int argc, char *argv[]) {
   int i, j, N, startLine, endLine, numOfThreads, numOfLines, id;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * N * sizeof(int));
   B = (int *)malloc(N * N * sizeof(int));
   C = (int *)malloc(N * N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Addition of matrices using OpenMP (2/3)

```
#pragma omp parallel shared(N) private(i, j, id, numOfThreads, numOfLines, startLine, endLine)
{
   id = omp_get_thread_num();
   numOfThreads = omp_get_num_threads();

   numOfLines = N / numOfThreads;
   startLine = numOfLines * id;

   if (id != numOfThreads - 1) {
        endLine = startLine + numOfLines;
   } else {
        endLine = N;
   }

   for (i = startLine; i < endLine; i++) {
        for (j = 0; j < N; j++) {
             C[i * N + j] = A[i * N + j] + B[j * N + j];
        }
   }
}  /* #pragma omp parallel ends here */
```

Addition of matrices using OpenMP (3/3)

```
    printf("C = ");
    for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
            printf("%d ", C[i * N + j]);
        }
        printf("\n");
    }

    return(0);
}  /* main() ends here */
```

Parallel initialization of vector

```
#include <omp.h>

void subdomain(float *x, int istart, int ipoints)
{
      int   i;
      for (i = 0; i < ipoints; i++)
            x[istart+i] = 123.456;
}

void sub(float *x, int npoints)
{
      int   iam, nt, ipoints, istart;

      #pragma omp parallel default(shared)
                private(iam,nt,ipoints,istart)
      {
            iam = omp_get_thread_num();
            nt  = omp_get_num_threads();

            /* size of partition */
            ipoints = npoints / nt;

            /* starting array index */
            istart = iam * ipoints;

            /* last thread may do more */
            if (iam == nt-1)
                  ipoints = npoints - istart;

            subdomain(x, istart, ipoints);
      }
}
```

```
int main()
{
      float array[10000];

      sub(array, 10000);

      return 0;
}
```

Work sharing constructs

The “parallel” construct assigns the same code to all threads

Usually we need to distribute work among more threads:

- Distribute iterations of a loop
- Parallel execution of different parts of the code

Available constructs in OpenMP

- Work sharing construct for loops
- “sections”

Work sharing construct for loops

#pragma omp for [clause [[,] clause]…] new-line

for-loops

"clause" can be one or more of the following:

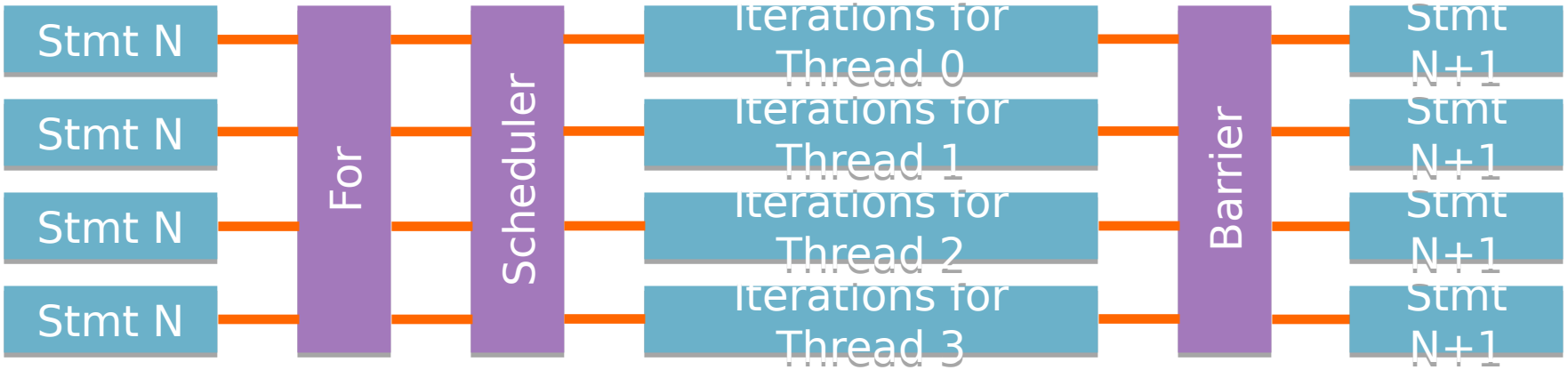
- private(list)
- firstprivate(list)
- lastprivate(list)
- reduction(operator : list)
- schedule(kind[, chunk_size])
- collapse(n)
- ordered
- nowait

Description

The “for” construct is probably the second most used directive in OpenMP

The iterations of the loop are distributed among preexisting threads

The “for” construct must be inside a parallel construct for parallel execution



Description

"lastprivate(*list*)"

All variables referenced in "list" become private variables per thread

At the end of the "*for*" construct, each variable is updated with the value that results from the execution of the last iteration of the loop

"nowait"

Threads will not wait at the implied barrier at the end of the "*for*" construct

Description

“ordered”

Declares that the iterations of the loop must be executed in the order that the serial code dictates

“collapse(*n*)”

Defines how many levels of a nested for-loop construct will be combined and distributed among the available threads

How are iterations distributed if more than one levels are requested to be collapsed?

OpenMP 4.5 Specification Document, pages 58-59

Description

"schedule(*kind[, chunk_size*])"

Defines how iterations of a loop are distributed among available threads of a parallel region

"static, chunk_size": Iterations are divided into smaller parts of size "chunk_size" (except the last one which can have less) and are assigned to threads in a round-robin fashion

"dynamic, chunk_size": Iterations are divided into smaller parts of size "chunk_size" (except the last one which can have less) and threads grab a new part dynamically, as soon as they finish with the previous part

"guided, chunk_size": Iterations are divided into smaller parts. The size of each part equals the number of unassigned iterations divided by the number of available threads. Each part is not allowed to have less than "chunk_size" iterations. The assignment of parts to threads is performed dynamically.

"auto" or "runtime"

Serial addition of vectors (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Serial addition of vectors (2/2)

```
   for (i = 0; i < N; i++) {
        C[i] = A[i] + B[i];
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        printf("%d ", C[i]);
   }

   return(0);
}  /* main() ends here */
```

Addition of vectors with OpenMP (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Addition of vectors with OpenMP (2/2)

```
   #pragma omp parallel
   {
   #pragma omp for
   for (i = 0; i < N; i++) {
        C[i] = A[i] + B[i];
   }
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        printf("%d ", C[i]);
   }

   return(0);
}  /* main() ends here */
```

Serial addition of matrices (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * N * sizeof(int));
   B = (int *)malloc(N * N * sizeof(int));
   C = (int *)malloc(N * N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Serial addition of matrices (2/2)

```
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             C[i * N + j] = A[i * N + j] + B[i * N + j];
        }
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             printf("%d ", C[i * N + j]);
        }
        printf("\n");
   }

   return(0);
}  /* main() ends here */
```

Addition of matrices with OpenMP (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * N * sizeof(int));
   B = (int *)malloc(N * N * sizeof(int));
   C = (int *)malloc(N * N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Addition of matrices with OpenMP (2/2)

```
   #pragma omp parallel private(j)
   #pragma omp for
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             C[i * N + j] = A[i * N + j] + B[i * N + j];
        }
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             printf("%d ", C[i * N + j]);
        }
        printf("\n");
   }

   return(0);
}  /* main() ends here */
```

Variation of matrix addition (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * N * sizeof(int));
   B = (int *)malloc(N * N * sizeof(int));
   C = (int *)malloc(N * N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Variation of matrix addition (2/2)

```
   for (i = 0; i < N; i++) {
        #pragma omp parallel
        #pragma omp for
        for (j = 0; j < N; j++) {
             C[i * N + j] = A[i * N + j] + B[i * N + j];
        }
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             printf("%d ", C[i * N + j]);
        }
        printf("\n");
   }

   return(0);
}  /* main() ends here */
```

Which version is better?

The first one divides matrices by rows

The second one divides matrices by columns

How many times are threads created in each case?

- How many times are threads joined?
- How many barriers are executed?

Lower triangular matrix x vector (1/2)

```
int *A, *B, *C;
int N, chunk;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 3) {
        printf("Provide the number of threads to create and the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);
   chunk = atoi(argv[2]);

   A = (int *)malloc(N * N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Lower triangular matrix x vector (2/2)

```
   /*
    * For all rows in the chunk.
    */
   #pragma omp parallel private(j)
   #pragma omp for schedule(dynamic, chunk)
   for (i = 0; i < N; i++) {
        C[i] = 0;
        /*
         * For all elements in the current row.
         */
        for (j = 0; j < i + 1; j++) {
            C[i] += (A[j] * B[j]);
        }
   }

   return(0);
} /* main() ends here */
```

Examples of “collapse”, “nowait” and “schedule” clauses

```
void sub()
{
      int   i, j, k;

      #pragma omp for collapse(2) private(i,j,k)
      for (k = kl; k <= ku; k += ks)
            for (j = jl; j <= ju; j += js)
                  for (i = il; i <= iu; i += is)
                        bar(a, i, j, k)
}
```

```
#include <math.h>

void a92(int n, float *a, float *b, float *c,
          float *y, float *z)
{
      int   i;
      #pragma omp parallel
      {
            #pragma omp for schedule(static)
nowait
            for (i=0; i<n; i++)
                  c[i] = (a[i] + b[i]) / 2.0;
            #pragma omp for schedule(static)
nowait
            for (i=0; i<n; i++)
                  z[i] = sqrt(c[i]);
            #pragma omp for schedule(static)
nowait
            for (i=1; i<=n; i++)
                  y[i] = z[i-1] + a[i];
      }
}
```

```
#include <math.h>

void a9(int n, int m, float *a, float *b,
         float *y, float *z)
{
      int   i;
      #pragma omp parallel
      {
            #pragma omp for nowait
            for (i=1; i<n; i++)
                  b[i] = (a[i] + a[i-1]) / 2.0;

            #pragma omp for nowait
            for (i=0; i<m; i++)
                  y[i] = sqrt(z[i]);
      }
}
```

The “sections” construct

Syntax of the “sections” construct

#pragma omp sections *[clause[[,] clause] …] new-line*

{

[#pragma omp section *new-line]*

structured-block

[#pragma omp section *new-line*

structured-block]

}

The “sections” construct

“clause” can be one or more of the following:

- private(list)
- firstprivate(list)
- lastprivate(list)
- reduction(operator : list)
- nowait

Composed of a set of “structured-blocks”

- Each one of them executes on a single thread

Example (1/2)

```
int *A, *B, *C, *D;
int N;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   D = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL) || (D == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Example (2/2)

```
#pragma omp parallel shared(A, B, C, D) private(i)
{
    #pragma omp sections nowait
    {

    #pragma omp section
    for (i = 0; i < N; i++)
        C[i] = A[i] + B[i];

    #pragma omp section
    for (i = 0; i < N; i++)
        D[i] = A[i] * B[i];

    }
} /* #pragma omp parallel ends here */
} /* main() ends here */
```

One thread executes this loop

One thread executes this loop

Example

```
void XAXIS();
void YAXIS();
void ZAXIS();

void a11()
{
#pragma omp parallel
    #pragma omp sections
    {
        #pragma omp
section
        XAXIS();

        #pragma omp
section
        YAXIS();

        #pragma omp
section
        ZAXIS();
    }
}
```

Combined parallelization and work sharing constructs

- Shortcuts to define a “parallel” and a work sharing construct together
  - The meaning is the same like having a “parallel” construct followed immediately by a work sharing construct
- Allowed clauses are the union of the clauses of the two constructs
  - With a few exceptions

The “parallel for” construct

#pragma omp parallel for [clause [[,] clause]…] new-line

for-loop

“clause” can be any clause of the “parallel” or the “for” construct

With the exception of “nowait”

Serial addition of vectors (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Serial addition of vectors (2/2)

```
   for (i = 0; i < N; i++) {
        C[i] = A[i] + B[i];
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        printf("%d ", C[i]);
   }

   return(0);
}  /* main() ends here */
```

Addition of vectors with OpenMP (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Addition of vectors with OpenMP (2/2)

```
   #pragma omp parallel for
   for (i = 0; i < N; i++) {
        C[i] = A[i] + B[i];
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        printf("%d ", C[i]);
   }

   return(0);
}  /* main() ends here */
```

Serial addition of matrices (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * N * sizeof(int));
   B = (int *)malloc(N * N * sizeof(int));
   C = (int *)malloc(N * N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Serial addition of matrices (2/2)

```
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             C[i * N + j] = A[i * N + j] + B[i * N + j];
        }
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             printf("%d ", C[i * N + j]);
        }
        printf("\n");
   }

   return(0);
}  /* main() ends here */
```

Addition of matrices with OpenMP (1/2)

```
int *A, *B, *C;
int N;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * N * sizeof(int));
   B = (int *)malloc(N * N * sizeof(int));
   C = (int *)malloc(N * N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Addition of matrices with OpenMP (2/2)

```
   #pragma omp parallel for private(j)
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             C[i * N + j] = A[i * N + j] + B[i * N + j];
        }
   }

   printf("C = ");
   for (i = 0; i < N; i++) {
        for (j = 0; j < N; j++) {
             printf("%d ", C[i * N + j]);
        }
        printf("\n");
   }

   return(0);
}  /* main() ends here */
```

The “parallel sections” construct

Syntax of the “parallel sections” construct

#pragma omp parallel sections *[clause[[,] clause] …] new-line*

{

[#pragma omp section *new-line]*

structured-block

[#pragma omp section *new-line*

structured-block]

}

“clause” can be any clause of the “parallel” or the “sections” construct

With the exception of “nowait”

Example (1/2)

```
int *A, *B, *C, *D;
int N;

int main(int argc, char *argv[]) {
   int i, j;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   C = (int *)malloc(N * sizeof(int));
   D = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL) || (C == NULL) || (D == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Example (2/2)

```
    #pragma omp parallel sections shared(A, B, C, D) private(i)
    {

        #pragma omp section
        for (i = 0; i < N; i++)
            C[i] = A[i] + B[i];

        #pragma omp section
        for (i = 0; i < N; i++)
            D[i] = A[i] * B[i];

    } /* #pragma omp parallel sections ends here */
} /* main() ends here */
```

Example

```
void XAXIS();
void YAXIS();
void ZAXIS();

void a11()
{
#pragma omp parallel sections
{
    #pragma omp section
    XAXIS();

    #pragma omp section
    YAXIS();

    #pragma omp section
    ZAXIS();
}
}
```

The “master” construct

#pragma omp master new-line

structured-block

Only the master thread executes the “structured-block”

If nested parallelism is supported

It applies to the innermost team of threads that has been created

There is no barrier at the end of the construct

In contrast to the “single” construct

Example

```
#include <stdio.h>

extern float average(float,float,float);

void a15( float* x, float* xold, int n, float tol )
{
     int       c, i, toobig;
     float     error, y;

     c = 0;
#pragma omp parallel
{
     do {
          #pragma omp for private(i)
          for( i = 1; i < n-1; ++i ) {
               xold[i] = x[i];
          }

          #pragma omp single
          {
               toobig = 0;
          }
          #pragma omp for private(i,y,error) \
                          reduction(+:toobig)
          for( i = 1; i < n-1; ++i ) {
               y = x[i];
               x[i] = average( xold[i-1], x[i],
                               xold[i+1] );
               error = y - x[i];
               if( error > tol || error < -tol )
                    ++toobig;
          }

          #pragma omp master
          {
               ++c;
               printf( "iteration %d, toobig=%d\n",
                         c, toobig );
          }
     } while( toobig > 0 );
}
}
```

The “single” construct

#pragma omp single [clause[[,] clause] …] new-line

structured-block

“clause” can be one or more of the following:

- private(list)
- firstprivate(list)
- copyprivate(list)
- nowait

Description

The “single” construct defines that the corresponding “*structured-block*” will be executed only by one thread of the team

- Not necessarily the master thread

The rest of the threads of the team wait on a barrier at the end of the “single” construct

- Except if the clause “nowait” has been used

Example

```
#include <stdio.h>

void work1() {}
void work2() {}

void a12()
{
     #pragma omp parallel
     {
          #pragma omp single
          printf("Beginning work1.\n");

          work1();

          #pragma omp single
          printf("Finishing work1.\n");

          #pragma omp single nowait
          printf("Finished work1 and beginning work2.\n");

          work2();
     }
}
```

The “critical” construct

#pragma omp critical [(name)] new-line

structured-block

The “structured-block” is executed only by a single thread at any point in time

But all threads encountering the construct will eventually execute it

It does not matter to which team each thread belongs

An optional name can be given to each “critical” construct

Only threads that use the same name participate in the mutual exclusion

All threads that don’t use a name participate in a default “critical” construct

This construct does not have a name

Multiplication of vectors (1/2)

```
int *A, *B, res = 0;
int N;

int main(int argc, char *argv[]) {
   int i;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Multiplication of vectors (2/2)

```
   #pragma omp parallel for
   for (i = 0; i < N; i++) {
        #pragma omp critical
        res += (A[i] * B[i]);
   }

   printf("Result is %d\n", res);

   return(0);
} /* main() ends here */
```

Example

```
int dequeue(float *a);
void work(int i, float *a);

void a16(float *x, float *y)
{
   intix_next, iy_next;
   #pragma omp parallel shared(x, y) private(ix_next,
iy_next)
   {
      #pragma omp critical(xaxis)
         ix_next = dequeue(x);
      work(ix_next, x);

      #pragma omp critical(yaxis)
         iy_next = dequeue(y);
      work(iy_next, y);
   }
}
```

The “atomic” construct

#pragma omp atomic new-line

expression-stmt

Declares that a memory location must be updated atomically

“expression-stmt” can be:

x++, ++x, x--, --x

x *binop*= *expr*

binop: +, -, *, /, &, |, ^, <<, >>

Cannot be an overloaded operator (C++)

Only the update of the memory location is atomic

The calculation of “*expr*” is not atomic

Multiplication of vectors (1/2)

```
int *A, *B, res = 0;
int N;

int main(int argc, char *argv[]) {
   int i;

   if (argc != 2) {
        printf("Provide the problem size.\n");
        exit(0);
   }

   N = atoi(argv[1]);

   A = (int *)malloc(N * sizeof(int));
   B = (int *)malloc(N * sizeof(int));
   if ((A == NULL) || (B == NULL)) {
        printf("Could not allocate memory.\n");
        exit(0);
   }
```

Multiplication of vectors (2/2)

```
   #pragma omp parallel for
   for (i = 0; i < N; i++) {
        #pragma omp atomic
        res += (A[i] * B[i]);
   }

   printf("Result is %d\n", res);

   return(0);
} /* main() ends here */
```

An even better solution...

```
   #pragma omp parallel for reduction(+:res)
   for (i = 0; i < N; i++) {
        res += (A[i] * B[i]);
   }

   printf("Result is %d\n", res);

   return(0);
} /* main() ends here */
```

Example

```
float work1(int i)
{
     return 1.0 * i;
}

float work2(int i)
{
     return 2.0 * i;
}

void a19(float *x, float *y, int *index, int n)
{
     int  i;

     #pragma omp parallel for shared(x, y, index, n)
     for (i=0; i<n; i++) {
          #pragma omp atomic
          x[index[i]] += work1(i);

          y[i] += work2(i);
     }
}
```

```
int main()
{
     float     x[1000];
     float     y[10000];
     int       index[10000];
     int       i;

     for (i = 0; i < 10000; i++) {
          index[i] = i % 1000;
          y[i]=0.0;
     }

     for (i = 0; i < 1000; i++)
          x[i] = 0.0;

     a19(x, y, index, 10000);

     return 0;
}
```

The “barrier” construct

#pragma omp barrier new-line

- Declares a barrier at the point where the construct appears
- It operates on the threads of the current team
- If nested parallelism is supported
  - It refers to the innermost team of threads that has been created

Example

```
void work(int n) {}

void sub3(int n)
{
     work(n);
     #pragma omp barrier
     work(n);
}

void sub2(int k)
{
     #pragma omp parallel shared(k)
     sub3(k);
}

void sub1(int n)
{
     int  i;

     #pragma omp parallel private(i) shared(n)
     {
          #pragma omp for
          for (i=0; i<n; i++)
               sub2(i);
     }
}
```

```
int main()
{
     sub1(2);
     sub2(2);
     sub3(2);

     return 0;
}
```

Handling data dependencies

Data dependencies in loops

There is a data dependence between two instructions S_1 and S_2 when they access the same memory location

- In the same iteration of the loop
  - *Loop-Independent Dependencies*
- During different iterations of the loop
  - *Loop-Carried Dependencies*

Parallelization

A loop can be easily parallelized when there are no data dependencies

- Typical use of parallelization constructs, like #pragma omp parallel for

Otherwise it can be parallelized:

- If it can be converted into a form where parallelization is possible
- Using another parallelization approach
- Using tasks where data dependencies can be expressed (see “task” struct using clause depend(in/out/inout) in OpenMP >= 4.0)

Example

```
#define N   1000

void testParallelization() {
   double V[N];
   int i;

   #pragma omp parallel for shared(V) private(i) schedule(static)
   for (i = 0; i < N - 1; i++) {
        V[i] = (V[i] + V[i+1]) / 2.0;
   }
}
```

First correct approach

```
#define N   1000

void testParallelization() {
   double V[N], oldV[N];
   int i;

   #pragma omp parallel shared(V, oldV) private(i) schedule(static)
   {
        #pragma omp for
        for (i = 0; i < N; i++) {
             oldV[i] = V[i];
        }

        #pragma omp for
        for (i = 0; i < N - 1; i++) {
             V[i] = (V[i] + oldV[i+1]) / 2.0;
        }
   }
}
```

A better solution (1/2)

```
#define N   1000

void testParallelization() {
   double V[N], border;
   int i, s, id, nt, limitL, limitR;

   #pragma omp parallel shared(V) private(i,s,id,nt,limitL,limitR,border)
   {
        id = omp_get_thread_num();
        nt = omp_get_num_threads();
        s  = N / nt; /* We assume that they divide exactly. */

        limitL = id * s;
        limitR = limitL + s - 1;

        if (id != nt - 1) {
             border = V[limitR+1];
        }

        #pragma omp barrier
```

A better solution (2/2)

```
        for (i = limitL; i < limitR; i++) {
             V[i] = (V[i] + V[i+1]) / 2.0;
        }

        if (id != nt - 1) {
             V[limitR] = (V[limitR] + border) / 2.0;
        }
   }
}
```

What happens in this case?

```
#define N   1000

void testParallelization() {
   double V[N];
   int i;

   for (i = 1; i < N; i++) {
        V[i] = (V[i-1] + V[i]) / 2.0;
   }
}
```

Functions of the Run-Time Library

Run-Time Library Routines

Prototypes of functions are declared in <omp.h>

Furthermore definitions of data types

“omp_lock_t”

To declare variables for mutual exclusion

“omp_nest_lock_t”

To declare variables for mutual exclusion that support nesting

“omp_sched_t”

To declare variables that control how iterations of a loop are distributed among threads

Number of threads and thread identification

void omp_set_num_threads(int *num_threads*);

Defines the number of threads to be created in following “parallel” constructs

If these don’t use the “num_threads” clause

int omp_get_num_threads(void)*;*

Returns the number of threads that compose the current team

int omp_get_thread_num(void)*;*

Returns the ID of the thread within a team

IDs are in the range from 0 up to and including omp_get_num_threads() – 1

int omp_get_max_threads(void)*;*

Returns the maximum allowed number of threads to be created in a “parallel” construct

Dynamic adjustment and nesting of parallelism

void omp_set_dynamic(int *dynamic_threads*);

Enables or disables dynamic adjustment of the number of threads available for the execution of subsequent parallel regions

Sets the ICV dyn-var to either true or false

int omp_get_dynamic(void);

Returns the current value of the ICV *dyn-var*

void omp_set_nested(int *nested*);

Enables or disables nested parallelism

Sets the ICV nest-var to either true or false

int omp_get_nested(void);

Returns the current value of the ICV *nest-var*

Retrieving information about nested parallelism

void omp_set_max_active_levels (int max_levels);

Sets the maximum allowed depth for creating nested parallelism

int omp_get_max_active_levels(void);

Returns the maximum allowed depth for creating nested parallelism

int omp_get_level(void);

Returns the number of nested “parallel” constructs that the calling task has encountered

Constructs might be active or inactive

int omp_get_active_level(void);

Returns the number of nested “parallel” constructs that the calling task has encountered

Counts only active levels

Retrieving information about parallel constructs

int omp_in_parallel(void);

Returns true if the routine is called within a parallel region

Otherwise it returns false

int omp_get_team_size(int level);

Returns the number of threads that compose a team at level "*level*" of nested parallel regions

int omp_get_ancestor_thread_num(int level);

Returns the ID of the ancestor thread at level "l*evel*" of nested parallel regions

Other routines

void omp_set_schedule(omp_sched_t kind, int modifier);

Sets the algorithm for distributing work among threads

static, dynamic, guided: modifier defines the size of chunk

auto: modifier is ignored

void omp_get_schedule(omp_sched_t *kind, int *modifier);

Returns the currently used algorithm for distributing work among threads

int omp_get_num_procs(void);

Returns the number of processors available for executing the application

int omp_get_thread_limit(void);

Returns the maximum number of threads that an OpenMP application is allowed to create

Lock routines

The Run-Time Library includes a set of routines for handling mutual exclusion and synchronization

- They operate on synchronization variables

Allowed states of synchronization variables

- Uninitialized
- Unlocked
- Locked

Lock routines

There are two types of synchronization variables

- Simple locks
  - *If a thread locks a variable, the variable cannot be locked by any other thread*
- Nestable locks
  - *If a thread locks a variable, the variable can be locked again multiple times by the same thread*
    - *But not by another thread*

Initialization of synchronization variables

```
void omp_init_lock(omp_lock_t *lock);
void omp_init_nest_lock(omp_nest_lock_t *lock);
```

Destruction of synchronization variables

void omp_destroy_lock(omp_lock_t *lock);

void omp_destroy_nest_lock(omp_nest_lock_t *lock);

These routines ensure that the synchronization variable is set to the “Uninitialized” state

Locking of synchronization variables

void omp_set_lock(omp_lock_t *lock);

void omp_set_nest_lock(omp_nest_lock_t *lock);

If the case of a simple synchronization variable

The variable becomes “Locked” only if it previously was “Unlocked”

If the case of a nestable synchronization variable

The variable becomes “Locked” if it previously was “Unlocked”

The variable remains “Locked” if it previously was “Locked” and the routine is executed by the same task

Nesting level is increased by one

Unlocking of synchronization variables

void omp_unset_lock(omp_lock_t *lock);

void omp_unset_nest_lock(omp_nest_lock_t *lock);

If the case of a simple synchronization variable

- The variable becomes “Unlocked”

If the case of a nestable synchronization variable

- Nesting level is decreased by one
- If it reaches zero, the variable becomes “Unlocked”

Trying to lock and testing

int omp_test_lock(omp_lock_t *lock);

int omp_test_nest_lock(omp_nest_lock_t *lock);

These routines attempt to set an OpenMP lock

They do not suspend execution of the task executing the routine

omp_test_lock(): Returns “true” if the call actually locks the variable, otherwise “false”

omp_test_nest_lock(): Returns the current level of nesting if the call actually locks the variable, otherwise 0

Example

```
#include <omp.h>

typedef struct {
     int               a, b;
     omp_nest_lock_t   lck;
} pair;

int work1();
int work2();
int work3();

void incr_a(pair *p, int a)
{
     /* Called only from incr_pair, no lock. */
     p->a += a;
}

void incr_b(pair *p, int b)
{
     /* Called both from incr_pair and elsewhere, */
     /* so need a nestable lock. */
     omp_set_nest_lock(&p->lck);
     p->b += b;
     omp_unset_nest_lock(&p->lck);
}
```

```
void incr_pair(pair *p, int a, int b)
{
     omp_set_nest_lock(&p->lck);
     incr_a(p, a);
     incr_b(p, b);
     omp_unset_nest_lock(&p->lck);
}

void a45(pair *p)
{
     #pragma omp parallel sections
     {
          #pragma omp section
          incr_pair(p, work1(), work2());

          #pragma omp section
          incr_b(p, work3());
     }
}
```

Timing routines

double omp_get_wtime(void);

Returns elapsed wall clock time in seconds

double omp_get_wtick(void);

Returns the precision of the timer used by omp_get_wtime()

Environment variables

Environment variables

They affect the values of ICVs

Changes to environment variables after execution of an OpenMP application has started are ignored

Even if the changes are performed by the application itself

OMP_SCHEDULE

Ελέγχει τον τρόπο διαμοίρασης επαναλήψεων σε νήματα και το μέγεθος του chunk

Η τιμή της μεταβλητής έχει την μορφή

type[,chunk]

“type” μπορεί να είναι:

static, dynamic, guided, auto

“chunk” είναι προαιρετικό

Καθορίζει το μέγεθος κάθε chunk

Παράδειγμα χρήσης

export OMP_SCHEDULE=“guided,4”

export OMP_SCHEDULE=“dynamic”

OMP_NUM_THREADS

Controls the number of threads that will be created in a “parallel” construct

The value of the variable must be a positive integer

Usage example

```
export OMP_NUM_THREADS=16
```

OMP_DYNAMIC

controls dynamic adjustment of the number of threads to use for executing parallel regions

The value of the variable must be either “true” or “false”

If “true”

The OpenMP implementation may adjust the number of threads to use for executing parallel regions in order to optimize the use of system resources

Usage example

```
export OMP_DYNAMIC=true
```

OMP_NESTED

Controls whether actual creation of nested parallelism is allowed

The value of the variable must be either “true” or “false”

Usage example

```
export OMP_NESTED=true
```

OMP_STACKSIZE

Controls the size of the stack for threads created by the OpenMP implementation

The value of the variable can be:

size | size**B** | size**K** | size**M** | size**G**

If no suffix is used, the default size is in Kbytes

Usage examples

export OMP_STACKSIZE=2000500B

export OMP_STACKSIZE=3000k

export OMP_STACKSIZE="10 M"

export OMP_STACKSIZE=20000

OMP_WAIT_POLICY

Provides a hint to an OpenMP implementation about the desired behavior of waiting threads

The value of the variable can be either “ACTIVE” or “PASSIVE”

“ACTIVE”: Specifies that waiting threads should mostly be active, consuming processor cycles, while waiting.

“PASSIVE”: Specifies that waiting threads should mostly be passive, not consuming processor cycles, while waiting. For example, an OpenMP implementation may make waiting threads yield the processor to other threads or go to sleep.

Usage examples

```
export OMP_WAIT_POLICY=ACTIVE
export OMP_WAIT_POLICY=active
export OMP_WAIT_POLICY=PASSIVE
export OMP_WAIT_POLICY=passive
```

OMP_MAX_ACTIVE_LEVEL

controls the maximum number of nested active parallel regions

The value of the variable must be a positive integer

Usage example

```
export OMP_MAX_ACTIVE_LEVEL=4
```

OMP_THREAD_LIMIT

Sets the maximum number of OpenMP threads to use in a contention group

- Contention group: An initial thread and its descendent threads
- The value of the variable must be a positive integer

Usage example

```
export OMP_THREAD_LIMIT=200
```

Advanced features of OpenMP

The “task” struct

#pragma omp task [clause [[,] clause]…] new-line

structured-block

“clause” can be one or more of the following:

if (scalar-expression)

untied

default(shared | none)

private(list)

firstprivate(list)

shared(list)

Description

A new task is created

- From the code of the “*structured-block*”

Execution of the task can:

- Take place immediately
  - *On the thread that encountered the “task” struct*
- Be postponed
  - *Any thread of the team can execute the task*

It is possible to create nested tasks

- However, the newly created task is not part of the task that created it

Description

When an “if” clause exists

If “*scalar-expression*” evaluates to false

The thread that encounters the “task” struct immediately suspends its execution

The new task immediately starts its execution

The task that was suspended cannot resume execution until the new task finishes

Description

A thread can suspend execution of a task

- When it reaches a scheduling point

A suspended task will continue its execution at a later point in time on the same thread that suspended it

- Except if the “untied” clause has been specified
  - *Any thread of the team is allowed to select the suspended task and resume its execution*

Tree traversal (1/3)

```
struct node {
   /*
    * Here exist elements of the struct that
    * represent the data that each node stores.
    */
   struct node   *left;  /* NULL if there is no left  child. */
   struct node   *right; /* NULL if there is no right child. */
};

/*************************************************************/

struct node *build_tree() {
   struct node *root; /* Root node of the tree. */
   /*
    * Build a tree.
    * Return the root node to the caller.
    */

   return(root);
}
```

Tree traversal (2/3)

```
void process_node(struct node *curNode) {
   /*
    * Do cool stuff here with the data of the node.
    */
}

/*************************************************************/

void traverse(struct node *p) {
   if (p->left != NULL) {
        #pragma omp task  /* p is firstprivate by default */
        traverse(p->left);
   }

   if (p->right != NULL) {
        #pragma omp task  /* p is firstprivate by default */
        traverse(p->right);
   }

   process_node(p);
}
```

Tree traversal (3/3)

```
void main(int argc, char *argv[]) {
   struct node *root;

   root = build_tree();

   #pragma omp parallel
   {
        #pragma omp single
        {
             traverse(root);
        }
   }

   return(0);
} /* main() ends here */
```

The “taskwait” construct

#pragma omp taskwait new-line

Forces a task that has created more tasks to wait for the completion of all of them

Addition of data in a tree (1/3)

```
struct node {
   int        nodeData;
   struct node   *left;  /* NULL if there is no left  child. */
   struct node   *right; /* NULL if there is no right child. */
};

/************************************************************/

struct node *build_tree() {
   struct node *root; /* Root node of the tree. */
   /*
    * Build a tree.
    * Return the root node to the caller.
    */

   return(root);
}
```

Addition of data in a tree (2/3)

```
int traverse(struct node *p) {
   int  localSum, sumFromLeft = 0, sumFromRight = 0;

   if (p->left != NULL) {
        #pragma omp task  /* p is firstprivate by default */
        sumFromLeft  = traverse(p->left);
   }

   if (p->right != NULL) {
        #pragma omp task  /* p is firstprivate by default */
        sumFromRight = traverse(p->right);
   }

   #pragma omp taskwait

   localSum = sumFromLeft + sumFromRight + p->nodeData;

   return(localSum);
}
```

Addition of data in a tree (3/3)

```
void main(int argc, char *argv[]) {
   struct node   *root;
   int        sum;

   root = build_tree();

   #pragma omp parallel
   {
        #pragma omp single
        {
             sum = traverse(root);
        }
   }

   printf("Sum = %d\n", sum);

   return(0);
} /* main() ends here */
```

The “taskgroup” construct

#pragma omp taskgroup new-line

structured-block

Forces a task that has created more tasks to wait for the completion of all of them

As well as the completion of all tasks that have been created by its child tasks

OpenMP >= 4.0

Notice: The “taskwait” construct waits for completion only of its immediate “child-tasks” that it created

THANK YOU FOR YOUR ATTENTION

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