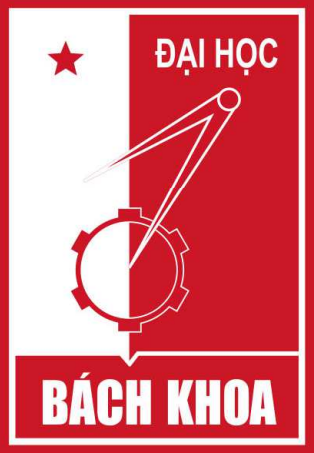

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Shared Memory Programming-OpenMP

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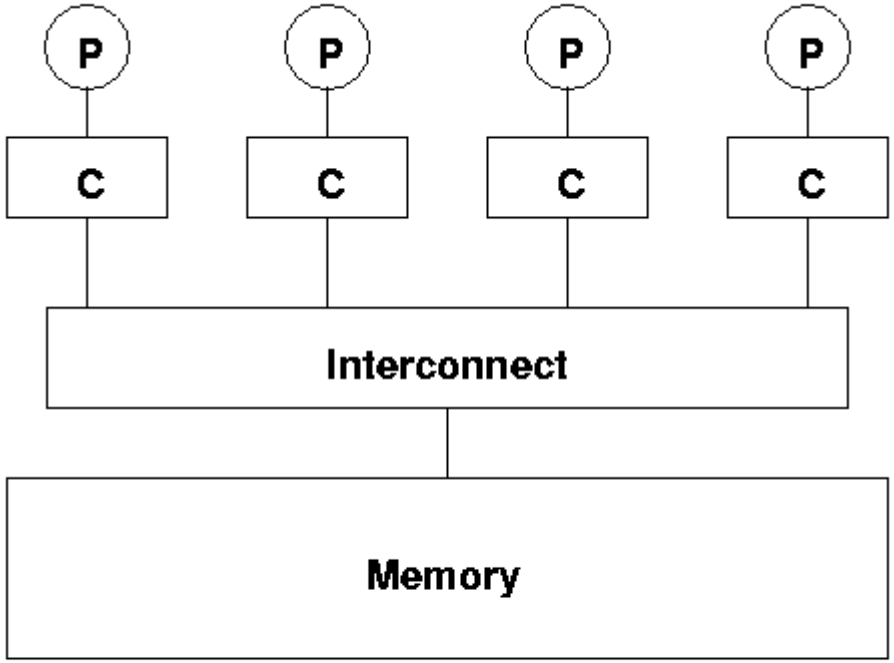
4.1 Shared Memory

Shared Memory Architecture

- All processors have access to one global memory
- All processors share the same address space
- The system runs a single copy of the OS
- Processors communicate by reading/writing to the global memory
- Examples: multiprocessor PCs (Intel P4), Sun Fire 15K, NEC SX-7, Fujitsu PrimePower, IBM p690, SGI Origin 3000.

Shared Memory Systems



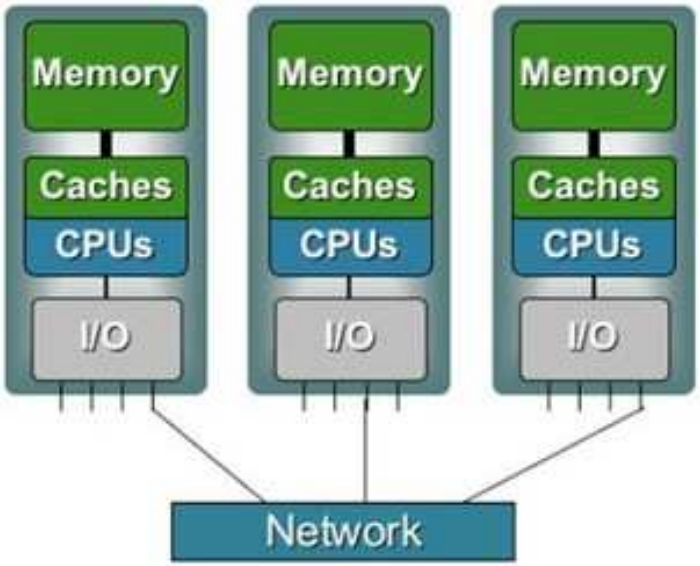
OpenMP

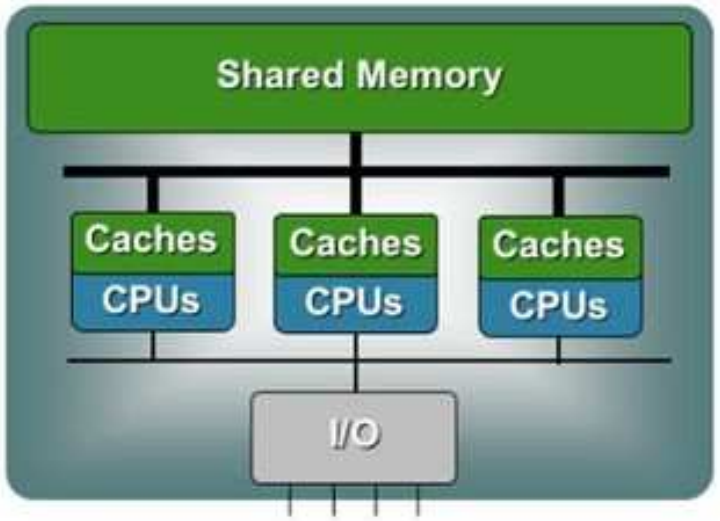
Pthreads

Shared memory

Shared Memory Systems (2)

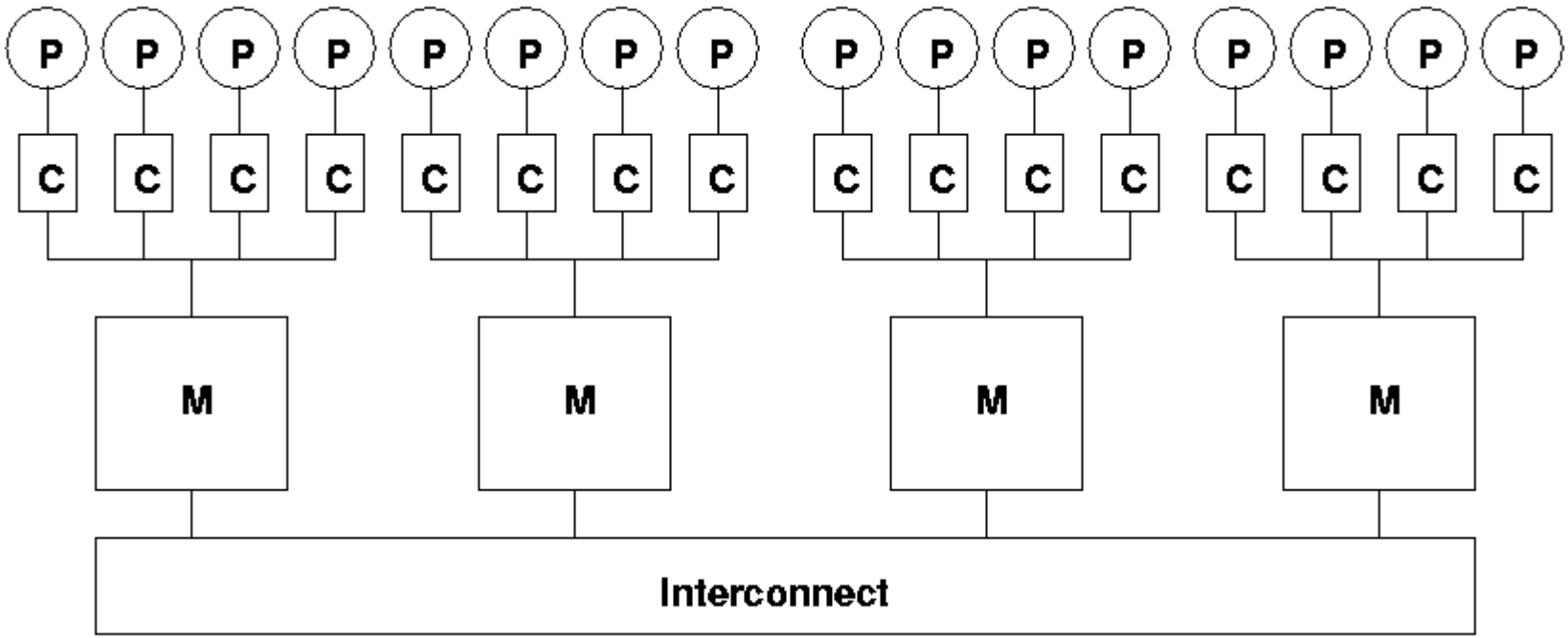
- All processors may access the whole main memory





- Non-UniformMemoryAccess
  - Memory access time is non-uniform
- UniformMemoryAccess
  - Memory access time is uniform

Clustered of SMPs



MPI

hybrid MPI + OpenMP

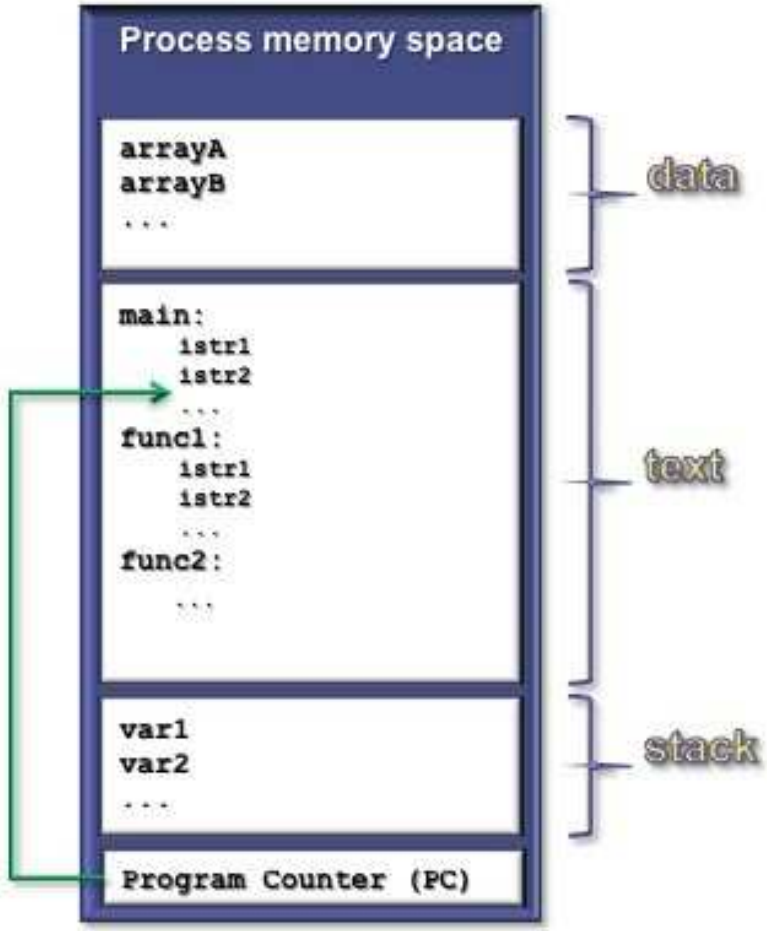
4.2 Multithread Programming

Shared Memory Programming

- Communication is implicitly specified
- Focus on constructs for expressing concurrency and synchronization
  - Minimize data-sharing overheads

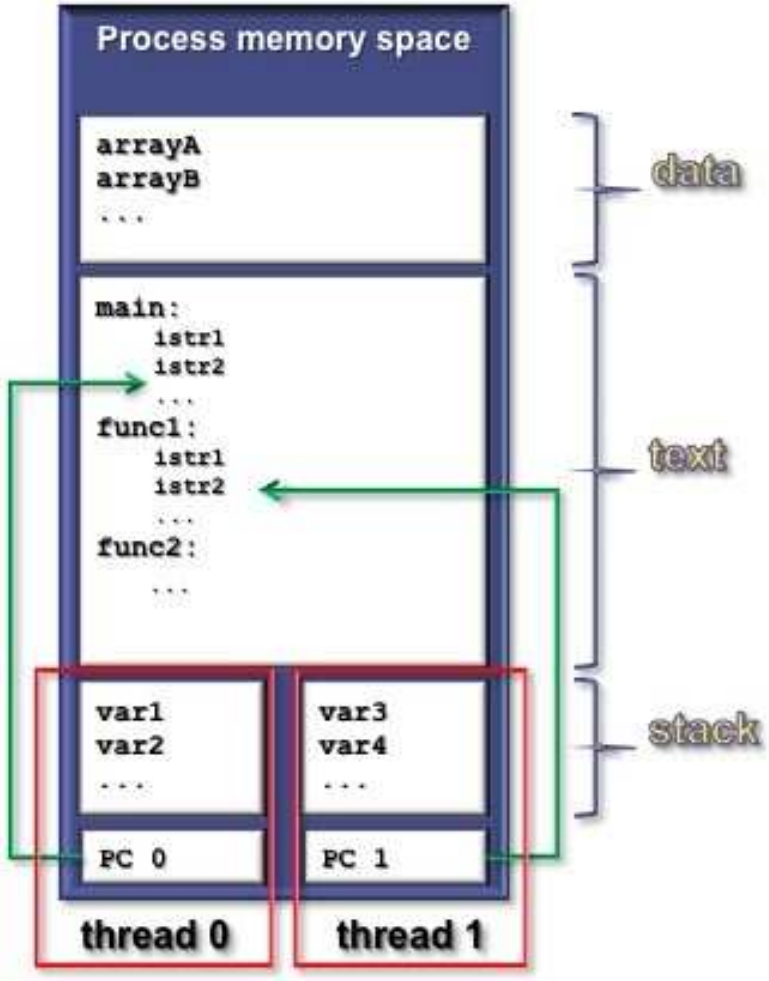
Process and thread

- A process is an instance of a computer program
- Information present in a process include:
  - Text
    - Machine code
  - Data
    - Global variables
  - Stack
    - Local variables
  - Program counter (PC)
    - A pointer to the istruction to be executed



Multi-threading

- The process contains several concurrent execution flows (threads)
  - Each thread has its own program counter (PC)
  - Each thread has its own private stack (variables local to the thread)
  - The instructions executed by a thread can access:
    - the process global memory (data)
    - the thread local stack



OpenMP vs. POSIX Threads

- POSIX threads is the other widely used shared programming API.
- Fairly widely available, usually quite simple to implement on top of OS kernel threads.
- Lower level of abstraction than OpenMP
  - library routines only, no directives
  - more flexible, but harder to implement and maintain
  - OpenMP can be implemented on top of POSIX threads
- Not much difference in availability
  - not that many OpenMP C++ implementations
  - no standard Fortran interface for POSIX threads

4.3 OPENMP

What is OpenMP?

- What does OpenMP stands for?
  - Open specifications for Multi Processing via collaborative work between interested parties from the hardware and software industry, government and academia.
- OpenMP is an Application Program Interface (API) that may be used to explicitly direct ***multi-threaded, shared memory parallelism.***
    - API components: Compiler Directives, Runtime Library Routines. Environment Variables
- OpenMP is a directive-based method to invoke parallel computations on share-memory multiprocessors

What is OpenMP?

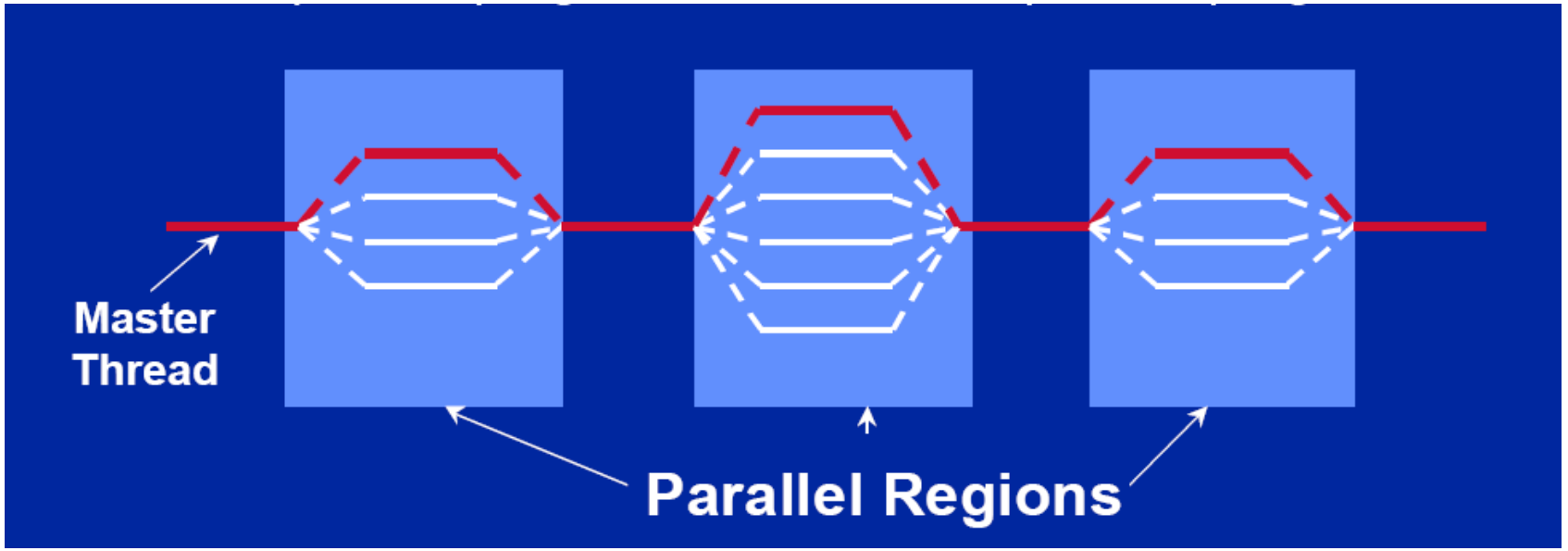
- OpenMP API is specified for C/C++ and Fortran.
- OpenMP is not intrusive to the original serial code: instructions appear in comment statements for fortran and pragmas for C/C++.
- OpenMP website: http://www.openmp.org
  - Materials in this lecture are taken from various OpenMP tutorials in the website and other places.

OpenMP Usage

- Applications
  - Applications with intense computational needs
  - From video games to big science & engineering
- Programmer Accessibility
  - From very early programmers in school to scientists to parallel computing experts
- Available to millions of programmers
  - In every major (Fortran & C/C++) compiler

Programming Model

- Fork-Join Parallelism:
  - Master thread spawns a team of threads as needed.
  - Parallelism is added incrementally: i.e. the sequential program evolves into a parallel program.



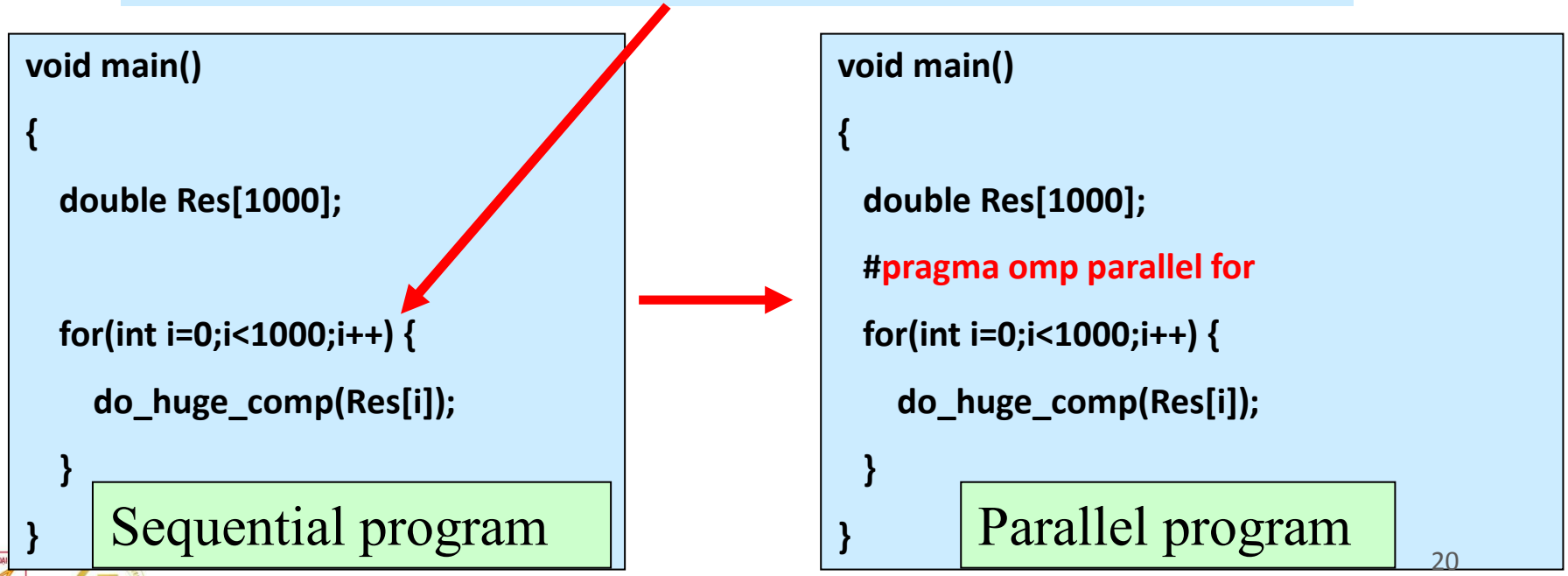
OpenMP Syntax

- Most of the constructs in OpenMP are compiler directives or pragmas.
  - For C and C++, the pragmas take the form:
    - #pragma omp *construct [clause [clause] …]*
  - For Fortran, the directives take one of the forms:
    - C$OMP *construct [clause [clause] …]*
    - !$OMP *construct [clause [clause] …]*
    - *$OMP *construct [clause [clause] …]*
- Since the constructs are directives, an OpenMP program can be compiled by compilers that don't support OpenMP.

OpenMP: How is OpenMP Typically Used?

- OpenMP is usually used to parallelize loops:
  - Find your most time consuming loops.
  - Split them up between threads.

Split-up this loop between multiple threads



How to compile and run OpenMP programs?

- Gcc 4.2 and above supports OpenMP 3.0
  - gcc –fopenmp a.c
  - Try example1.c
- To run: ‘a.out’
  - To change the number of threads:
    - setenv OMP_NUM_THREADS 4 (tcsh) or export OMP_NUM_THREADS=4(bash)

OpenMP:
How do Threads Interact?

- OpenMP is a shared memory model.
  - Threads communicate by sharing variables.
- Unintended sharing of data can lead to 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 stored to minimize the need for synchronization.

OpenMP Constructs

- OpenMP's constructs fall into 5 categories:
  - Parallel Regions
  - Worksharing
  - Data Environment
  - Synchronization
  - Runtime functions/environment variables
- OpenMP is basically the same between Fortran and C/C++

OpenMP: Parallel Regions

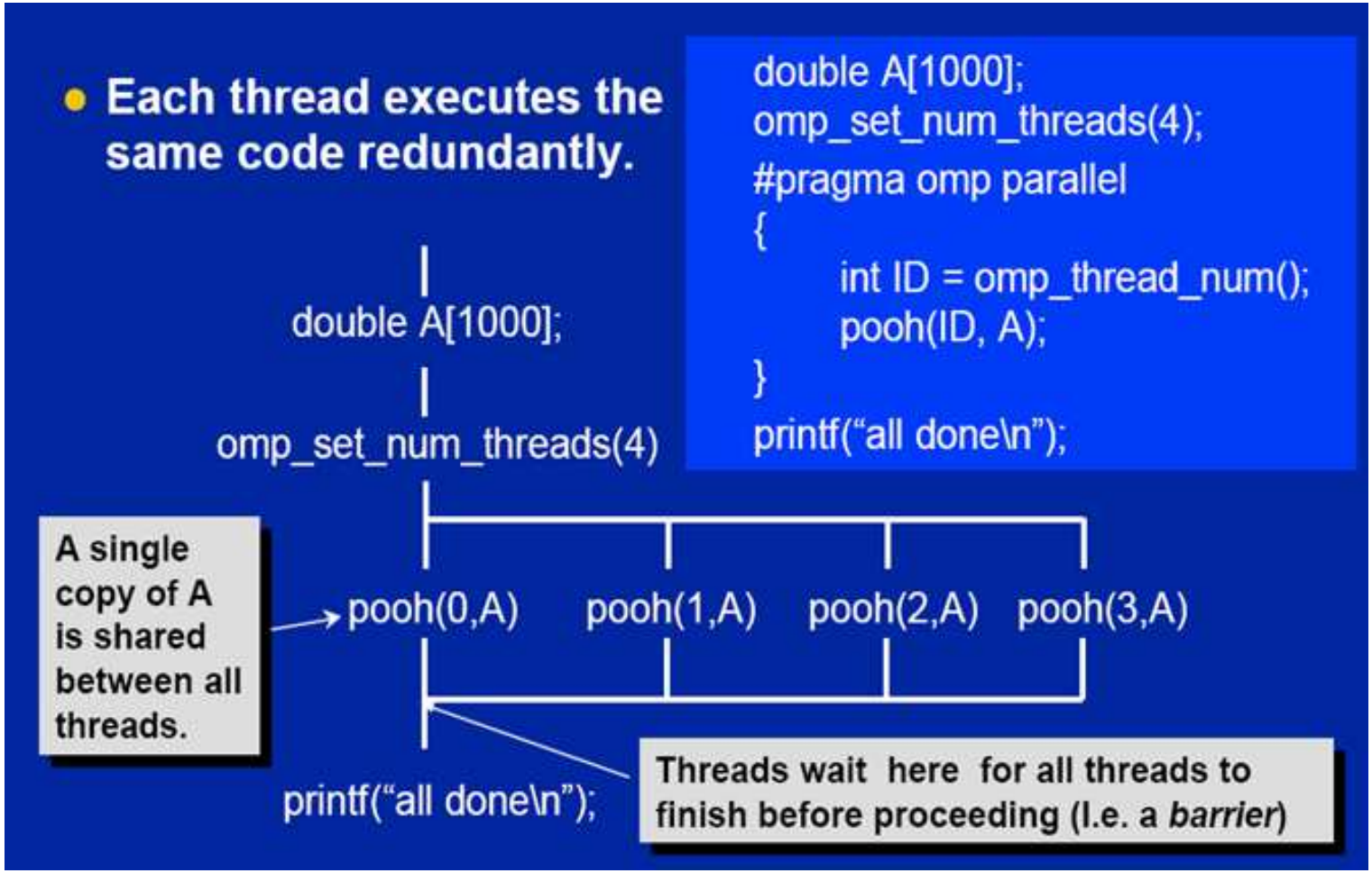
- You create threads in OpenMP with the "omp parallel" pragma.
- For example, To create a 4-thread Parallel region:

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
    int ID =omp_get_thread_num();
    pooh(ID,A);
}
```

Each thread redundantly executes the code within the structured block

- Each thread calls pooh(ID,A) for `ID` = `0` to `3`

Parallel Region



OpenMP: Work-Sharing Constructs

- The “for” Work-Sharing construct splits up loop iterations among the threads in a team

```
#pragma omp parallel
#pragma omp for
for (I=0;I<N;I++){
    NEAT_STUFF(I);
}
```

By default, there is a barrier at the end of the “omp for”. Use the “nowait” clause to turn off the barrier.

Work Sharing Constructs
A motivating example

Sequential code

```
for(i=0;I<N;i++) { a[i] = a[i] + b[i];}
```

OpenMP Parallel Region

```
#pragma omp parallel
{
    int id, i, Nthrds, istart, iend;
    id = omp_get_thread_num();
    Nthrds = omp_get_num_threads();
    istart = id * N / Nthrds;
    iend = (id+1) * N / Nthrds;
    for(i=istart;I<iend;i++) {a[i]=a[i]+b[i];}
}
```

OpenMP Parallel Region and a work-sharing for construct

```
#pragma omp parallel
#pragma omp for schedule(static)
for(i=0;I<N;i++) { a[i]=a[i]+b[i];}
```

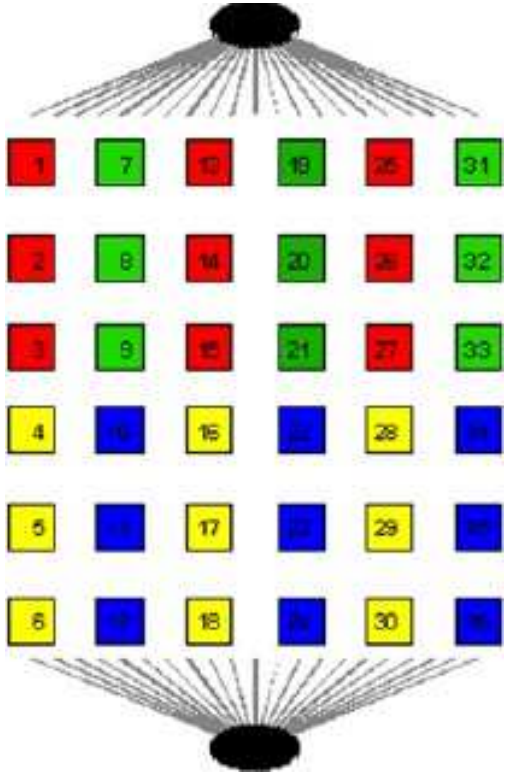
OpenMP For Construct:
The Schedule Clause

- The schedule clause effects how loop iterations are mapped onto threads
  - ◆schedule(static [,chunk])
    - Deal-out blocks of iterations of size “chunk” to each thread.
  - ◆schedule(dynamic[,chunk])
    - Each thread grabs “chunk” iterations off a queue until all iterations have been handled.
  - ◆schedule(guided[,chunk])
    - Threads dynamically grab blocks of iterations. The size of the block starts large and shrinks down to size “chunk” as the calculation proceeds.
  - ◆schedule(runtime)
    - Schedule and chunk size taken from the OMP_SCHEDULE environment variable.

static Scheduling

- Iterations are divided into chunks of size **`chunk`**, and the chunks are assigned to the threads in the team in a round-robin fashion in the order of the thread number
- It is the default schedule and the default **`chunk`** is approximately $N_{iter}/N_{threads}$
- For example:

```
!$omp parallel do &
!$omp schedule(static,3)
```

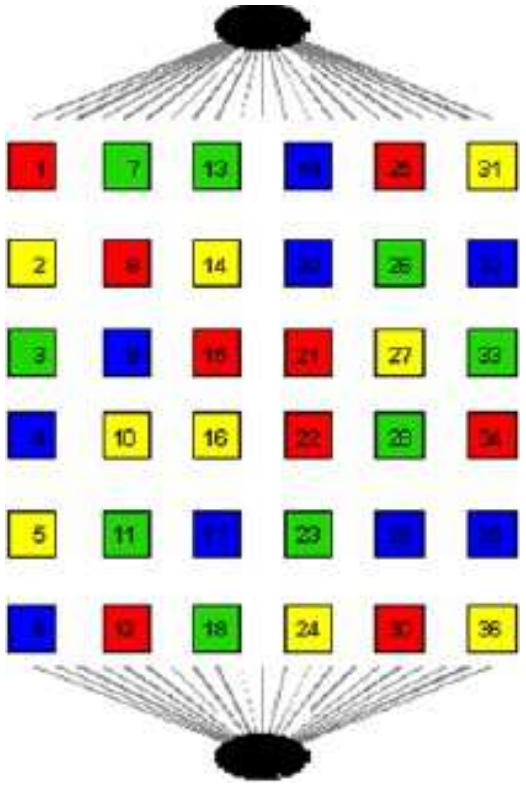


dynamic Scheduling

- Iterations are distributed to threads in the team in chunks as the threads request them. Each thread executes a **`chunk`** of iterations, then requests another **`chunk`**, until no chunks remain to be distributed.
- The default **`chunk`** is 1

- For example:

```
!$omp parallel do &
!$omp schedule(dynamic,1)
```

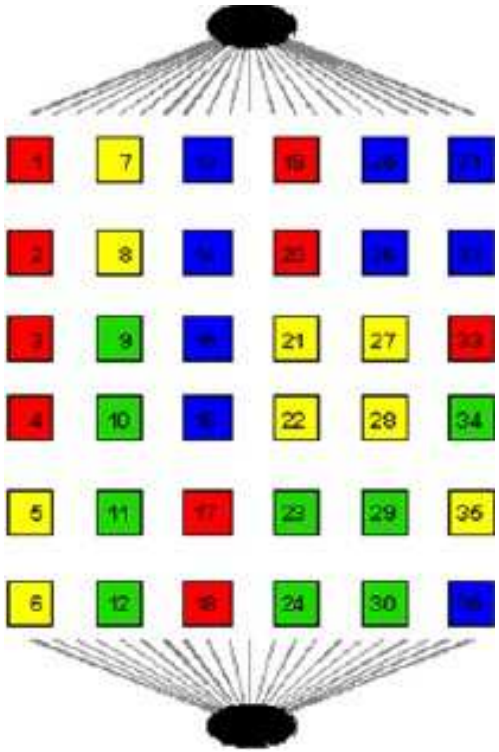


guided Scheduling

- Iterations are assigned to threads in the team in chunks as the executing threads request them. Each thread executes a chunk of iterations, then requests another chunk, until no chunks remain to be assigned. The chunk decreases to **`chunk`**
- The default value of **`chunk`** is 1

- For example:

```
!$omp parallel do &
!$omp schedule(guided,1)
```



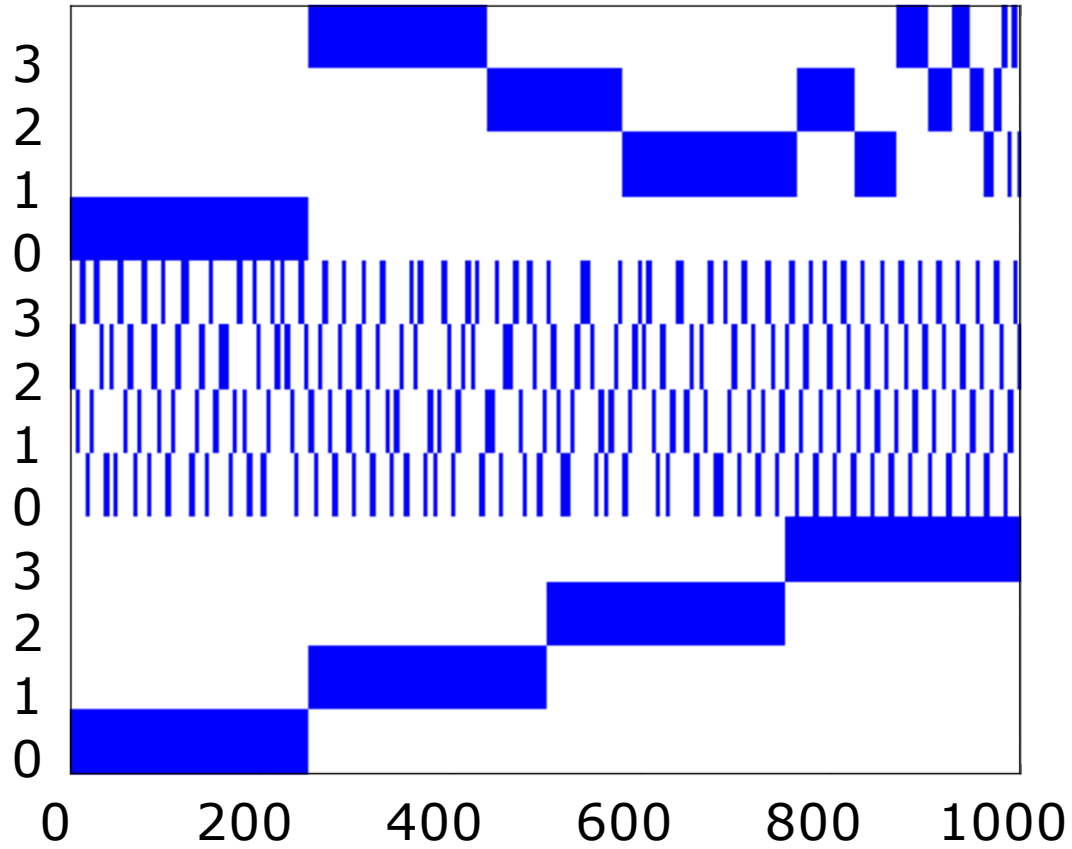
runtime and *auto* Scheduling

- **runtime**: iteration scheduling scheme is set at runtime through the enviroment variable **OMP_SCHEDULE**
  - For example:

    ```
    !$omp parallel do &
    !$omp schedule(runtime)
    ```

  - the scheduling scheme can be modified without recompiling the program changing the environment variable **OMP_SCHEDULE**, for example: **setenv OMP_SCHEDULE "dynamic,50"**
  - Only useful for experimental purposes during the parallelization
- **auto**: the decision regarding scheduling is delegated to the compiler and/or runtime system

Scheduling experiment



Different scheduling for a 1000 iterations loop with 4 threads: guided (top), dynamic (middle), static (bottom)

Sections: Work-Sharing Constructs

- The Sections work-sharing construct gives a different structured block to each thread.

```
#pragma omp parallel
#pragma omp sections
{
  X_calculation();
#pragma omp section
  y_calculation();
#pragma omp section
   z_calculation();
}
```

By default, there is a barrier at the end of the “omp sections”. Use the “nowait” clause to turn off the barrier.

Data-sharing attributes

- In a **`parallel`** construct the data-sharing attributes are *implicitily determined* by the **`default`** clause, if present
  - if no **`default`** clause is present they are shared
- Certain variables have a *predetermined* data-sharing attributes
  - Variables with automatic storage duration that are declared in a scope inside a construct are private
  - Objects with dynamic storage duration are shared
  - The loop iteration variable(s) in the associated for-loop(s) of a **`for`** construct is (are) private
  - A loop iteration variable for a sequential loop in a **`parallel`** construct is private in the innermost such construct that encloses the loop (only Fortran)
  - Variables with static storage duration that are declared in a scope inside the construct are shared
  - ...

Data-sharing attributes clauses

- *Explicitly determined* data-sharing attributes are those that are referenced in a given construct and are listed in a data-sharing attribute clause
  - **`shared(list)`**: there is only one istance of the objects in the list accessible by all threads in the team
  - **`private(list)`**: each thread has a copy of the variables in the list
  - **`firstprivate(list)`**: same as **`private`** but all variables in the list are initialized with the value that the original object had before entering the parallel construct
  - **`lastprivate(list)`**: same as **`private`** but the thread that executes the sequentially last iteration or section updates the value of the objects in the list
- The **`default`** clause sets the implicit default
  - **`default(none|shared)`** in C/C++

firstprivate

- Particular case of **private**.
  - Each private copy is initialized with the value of the variable of the **master** thread.

Example

```
void f() {
   int x= 17;
   #pragma omp parallel for firstprivate(x)
   for (long i=0;i<maxval;++i) {
      x+=i;       //xisinitially17
   }
   std::cout<<x<<std::endl;         //x==17
}
```

lastprivate

- Pass the value of the private variable of the last **sequential** iteration to the global variable.

Example

```
void f() {
   int x= 17;
   #pragma omp parallel for firstprivate(x) lastprivate(x)
   for (long i=0;i<maxval;++i) {
      x+=i;       //xisinitially17
   }
   std::cout<<x<<std::endl;        //xvalueiniterationi==maxval          −1
}
```

The `threadprivate` directive

C/C++

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

- Is a declarative directive
- Is used to create private copies of
  - *file-scope*, *namespace-scope* or **`static`** variables in C/C++
- Follows the variable declaration in the same program unit
- Initial data are undefined, unless the **`copyin`** clause is used

Data Environment:
Default Storage Attributes

- Shared Memory programming model:
  - Most variables are shared by default
- Global variables are SHARED among threads
  - Fortran: COMMON blocks, SAVE variables, MODULE variables
  - C: File scope variables, static
- But not everything is shared...
  - Stack variables in sub-programs called from parallel regions are PRIVATE
  - Automatic variables within a statement block are PRIVATE.

Private Clause

- private(var) creates a local copy of var for each thread.
  - The value is uninitialized
  - Private copy is *not* storage associated with the original

```
void wrong(){
    int IS = 0;
    #pragma parallel for private(IS)
    for(int J=1;J<1000;J++)
        IS = IS + J;
    printf("%i", IS);
}
```

OpenMP: Reduction

- Another clause that effects the way variables are shared:
  - reduction (op : list)
- The variables in “list” must be shared in the enclosing parallel region.
- Inside a parallel or a worksharing construct:
  - A local copy of each list variable is made and initialized depending on the “op” (e.g. 0 for “+”)
  - pair wise “op” is updated on the local value
  - Local copies are reduced into a single global copy at the end of the construct.

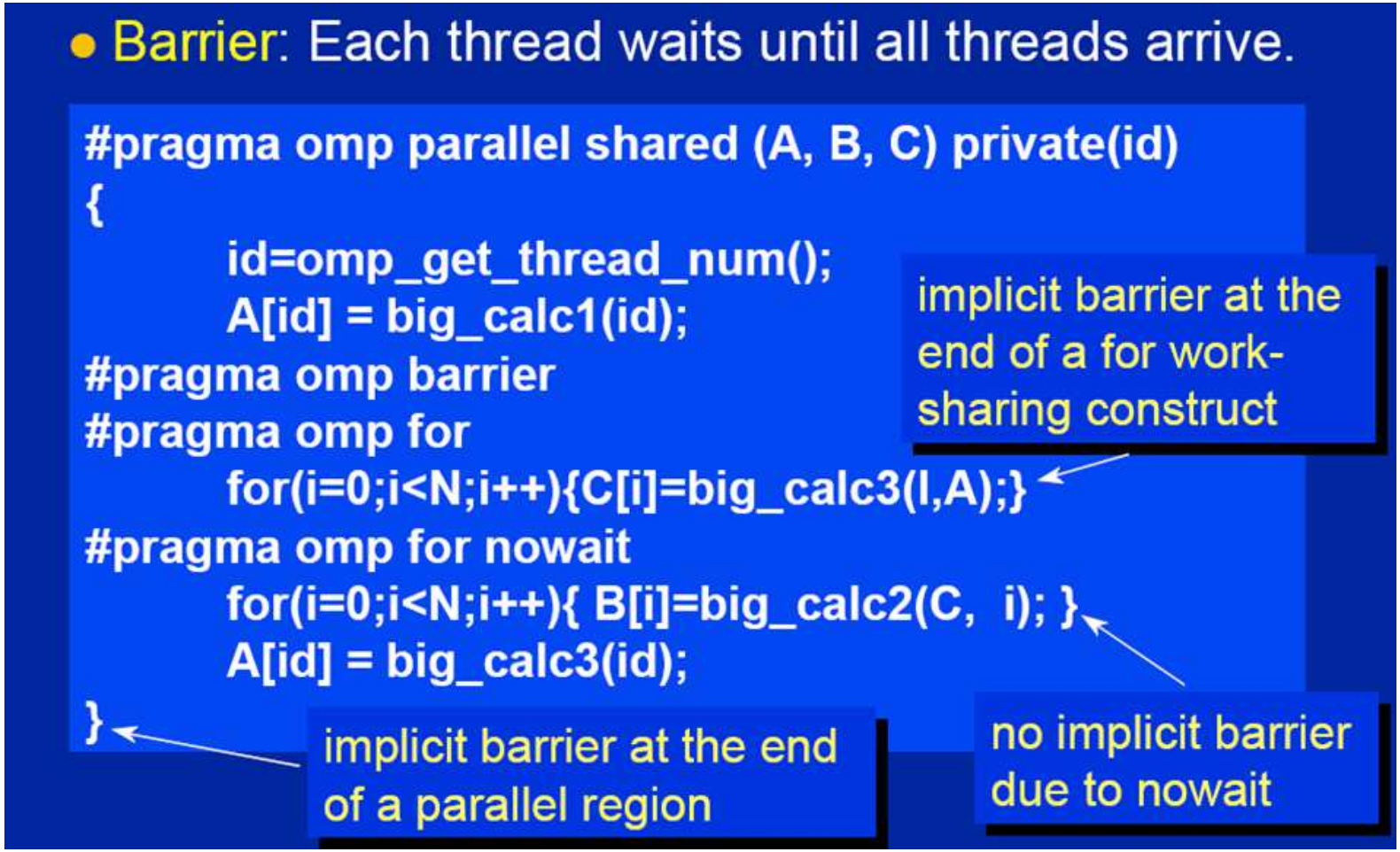
OpenMP:
An Reduction Example

```
#include <omp.h>
#define NUM_THREADS 2
void main ()
{
  int i;
  double ZZ, func(), sum=0.0;
  omp_set_num_threads(NUM_THREADS)
  #pragma omp parallel for reduction(+:sum)
  private(ZZ)
  for (i=0; i< 1000; i++){
        ZZ = func(i);
        sum = sum + ZZ;
  }
}
```

OpenMP: Synchronization

- OpenMP has the following constructs to support synchronization:
  - barrier
  - critical section
  - atomic
  - flush
  - ordered
  - single
  - master

Synchronization



`atomic` construct

- The **`atomic`** construct applies only to statements that update the value of a variable
  - Ensures that no other thread updates the variable between reading and writing
- The allowed instructions differ between Fortran and C/C++
  - Refer to the OpenMP specifications
- It is a special lightweight form of a **`critical`**
  - Only read/write are serialized, and only if two or more threads access the same memory address

C/C++

```
#pragma omp atomic [clause]
 <statement>
```

`atomic` Examples

C/C++

```
#pragma omp atomic update
x += n*mass; // default update

#pragma omp atomic read
v = x; // read atomically

#pragma omp atomic write
x = n*mass; write atomically

#pragma omp atomic capture
v = x++; // capture x in v and
         // update x atomically
```

Critical session

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

```
For(I=0; I<N; I++) {
   ……
   sum += A[I];
   ……
}
```

Cannot be parallelized if sum is shared.

Fix:

```
For(I=0; I<N; I++) {
   ……
   #pragma omp critical
   {
     sum += A[I];
   }
   ……
}
```

Master directive

- The master construct denotes a structured block that is only executed by the master thread. The other threads just skip it (no implied barriers or flushes).

```
#pragma omp parallel private (tmp)
{
  do_many_things();
  #pragma omp master
  { exchange_boundaries(); }
  #pragma barrier
  do_many_other_things();
}
```

Single directive

- The single construct denotes a block of code that is executed by only one thread.
- A barrier and a flush are implied at the end of the single block.

```
#pragma omp parallel private (tmp)
{
    do_many_things();
    #pragma omp single
    { exchange_boundaries(); }
    do_many_other_things();
}
```

Ordering

- An ordered region is executed in sequential order.

```
#pragma omp parallel
{
#pragma omp for ordered reduction(+:res)
for ( int i =0;i<max;++i) {
double tmp = f(i) ;
#pragma ordered
res += g(tmp);
}
}
```

Simple locks

- Locks in the OpenMP library.
- Also nested locks.

```
omp_lock_t l;
omp_init_lock(&l);
#pragma omp parallel
{
int id = omp_get_thread_num();
double x = f( i ) ;
omp_set_lock(&l);
cout << "ID=" << id << " tmp= " << tmp << endl;
omp_unset_lock(&l);
}
omp_destroy_lock(&l);
```

OpenMP: Library routines

- Lock routines
  - omp_init_lock(), omp_set_lock(), omp_unset_lock(), omp_test_lock()
- Runtime environment routines:
  - Modify/Check the number of threads
    - omp_set_num_threads(), omp_get_num_threads(), omp_get_thread_num(), omp_get_max_threads()
  - Turn on/off nesting and dynamic mode
    - omp_set_nested(), omp_set_dynamic(), omp_get_nested(), omp_get_dynamic()
  - Are we in a parallel region?
    - omp_in_parallel()
  - How many processors in the system?
    - omp_num_procs()

OpenMP: Environment Variables

- OMP_NUM_THREADS
  - bsh:
    - export OMP_NUM_THREADS=2
  - csh:
    - setenv OMP_NUM_THREADS 4

CODE. Matrix-vector multiply using a parallel loop and critical directive

```
/*** Spawn a parallel region explicitly scoping all variables ***/
#pragma omp parallel shared(a,b,c,nthreads,chunk)
private(tid,i,j,k)
{
  #pragma omp for schedule (static, chunk)
  for (i=0; i<NRA; i++)
    {
      printf("thread=%d did row=%d\n",tid,i);
      for(j=0; j<NCB; j++)
      for (k=0; k<NCA; k++)
        c[i][j] += a[i][k] * b[k][j];
    }
}
```

Ex.Travelling Salesman Problem

- The map is represented as a graph with nodes representing cities and edges representing the distances between cities.
- A special node (cities) is the starting point of the tour.
- Travelling salesman problem is to find the circle (starting point) that covers all nodes with the smallest distance.
- This is a well known NP-complete problem.

CODE. Sequential TSP

```
Init_q(); init_best();
While ((p = dequeue()) != NULL) {
    for each expansion by one city {
        q = addcity (p);
        if (complete(q)) {update_best(q);}
        else enqueue(q);
    }
}
```

CODE. OpenMP TSP

```
Do_work() {
  While ((p = dequeue()) != NULL) {
    for each expansion by one city {
        q = addcity (p);
        if (complete(q)) {update_best(q);}
        else enqueue(q);
    } } }
main() {
   init_q(); init_best();
   #pragma omp parallel for
   for (i=0; I < NPROCS; i++)
      do_work();
}
```

Summary

- OpenMP provides a compact, yet powerful programming model for shared memory programming
  - It is very easy to use OpenMP to create parallel programs.
- OpenMP preserves the sequential version of the program
- Developing an OpenMP program:
  - Start from a sequential program
  - Identify the code segment that takes most of the time.
  - Determine whether the important loops can be parallelized
    - The loops may have critical sections, reduction variables, etc
  - Determine the shared and private variables.
  - Add directives

Conclusion

- OpenMP is successful in small-to-medium SMP systems
- Multiple cores/CPUs dominate the future computer architectures; OpenMP would be the major parallel programming language in these architectures.
- Simple: everybody can learn it in 2 weeks
- Not so simple: Don’t stop learning! keep learning it for better performance

OpenMP discussion

- Ease of use
  - OpenMP takes cares of the thread maintenance.
    - Big improvement over pthread.
  - Synchronization
    - Much higher constructs (critical section, barrier).
    - Big improvement over pthread.

- OpenMP is easy to use!!

OpenMP discussion

- Expressiveness
  - Data parallelism:
    - MM and SOR
    - Fits nicely in the paradigm
  - Task parallelism:
    - TSP
    - Somewhat awkward. Use OpenMP constructs to create threads. OpenMP is not much different from pthread.

OpenMP discussion

- Exposing architecture features (performance):
  - Not much, similar to the pthread approach
    - Assumption: dividing job into threads = improved performance.
    - How valid is this assumption in reality?
      - Overheads, contentions, synchronizations, etc
  - This is one weak point for OpenMP: the performance of an OpenMP program is somewhat hard to understand.

OpenMP final thoughts

- Main issues with OpenMP: performance
  - Is there any obvious way to solve this?
    - Exposing more architecture features?
  - Is the performance issue more related to the fundamantal way that we write parallel program?
    - OpenMP programs begin with sequential programs.
    - May need to find a new way to write efficient parallel programs in order to really solve the problem.

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Thank you for your attentions !

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