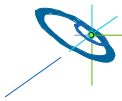
Introduction to OpenMP

University of Stuttgart
High Performance Computing Center Stuttgart (HLRS)
www.hlrs.de

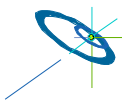
Matthias Müller,
Isabel Loebich, Rolf Rabenseifner

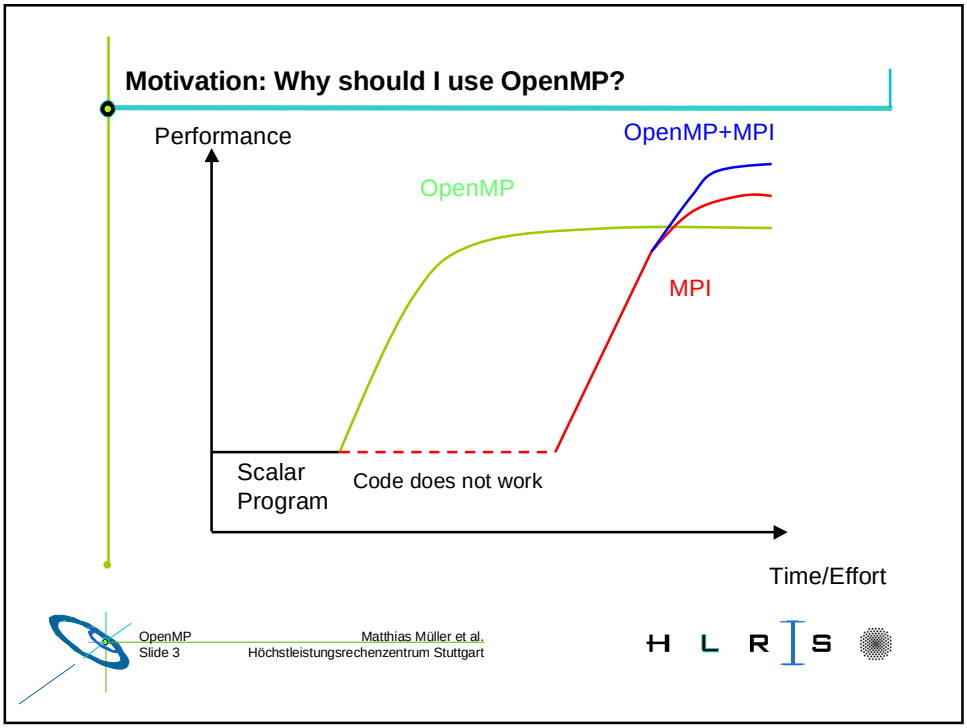
[mueller | loebich | rabenseifner] @hlrs.de



OpenMP Overview: What is OpenMP?

- Model for parallel programming
- Shared-memory parallelism
- Portable across shared-memory architectures
- Scalable
- Incremental parallelization
- Compiler based
- Extensions to existing programming languages
  - mainly by directives
  - a few library routines
- Fortran and C/C++ binding
- Supports data parallelism




Motivation: Why should I use OpenMP?
Performance
OpenMP+MPI
OpenMP
MPI
Scalar Program
Code does not work
Time/Effort
OpenMP
Slide 3
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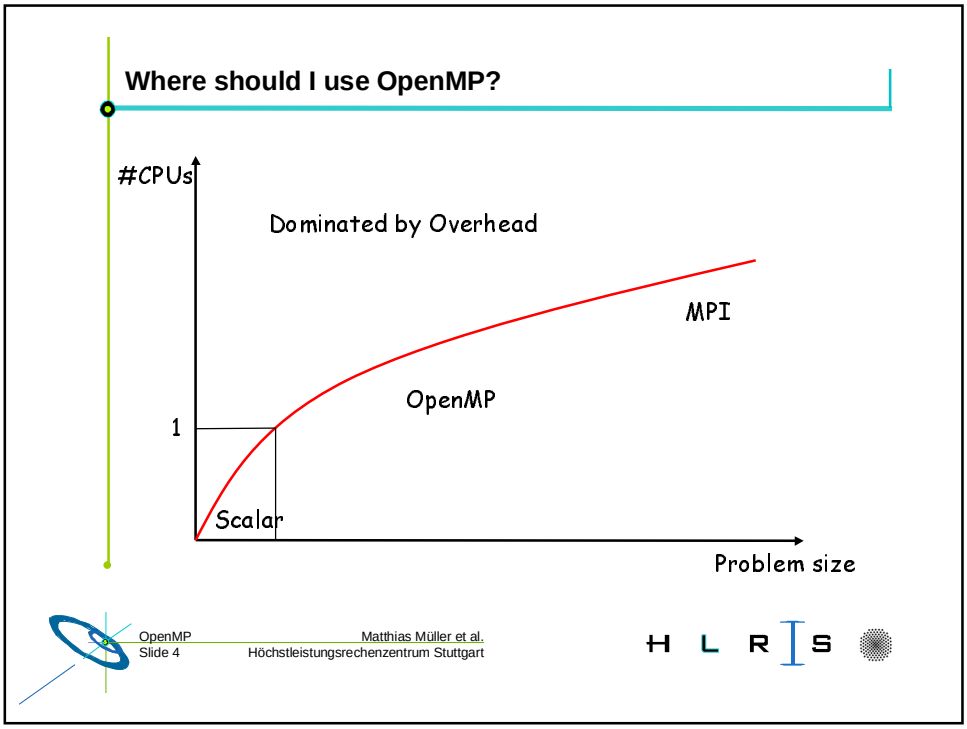
Where should I use OpenMP?
#CPUs
Dominated by Overhead
MPI
OpenMP
1
Scalar
Problem size
OpenMP
Slide 4
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Simple OpenMP Program

- Most OpenMP constructs are compiler directives or pragmas
- The focus of OpenMP is to parallelize loops
- OpenMP offers an incremental approach to parallelism

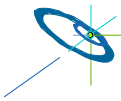
Serial Program:

```
void main()
{
   double Res[1000];

   for(int i=0;i<1000;i++) {
         do_huge_comp(Res[i]);
   }
}
```

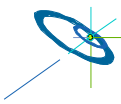
Parallel Program:

```
void main()
{
   double Res[1000];
#pragma omp parallel for
   for(int i=0;i<1000;i++) {
         do_huge_comp(Res[i]);
   }
}
```



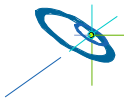
Outline

- Standardization Body: Who owns OpenMP?
- OpenMP Application Program Interface (API)
- Execution Model
  - **Parallel regions: team of threads**
  - **Syntax**
  - **Data environment (part 1)**
  - **Environment variables**
  - **Runtime library routines**
  - **Exercises and Compilation**
- Work-sharing directives
  - **Which thread executes which statement or operation?**
  - **Synchronization constructs, e.g., critical sections**
  - **Nesting and Binding**
- Data environment and combined constructs
  - **Private and shared variables**
  - **Combined parallel work-sharing directives**
- Summary of OpenMP API
- OpenMP Pitfalls



Who owns OpenMP? - OpenMP Architecture Review Board

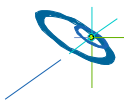
- ASCI Program of the US DOE
- Compaq Computer Corporation
- EPCC (Edinburgh Parallel Computing Center)
- Fujitsu
- Hewlett-Packard Company
- Intel Corporation
- International Business Machines (IBM)
- Kuck & Associates, Inc. (KAI)
- Silicon Graphics, Inc.
- Sun Microsystems, Inc



OpenMP timeline

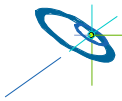
- OpenMP 1.0 for Fortran released October 1997
- OpenMP 1.0 for C/C++ released at October 1998
- OpenMP 1.1 for Fortran released at October 1999
- OpenMP 2.0 for Fortran released at November 2000
- OpenMP 2.0 for C/C++ to be released at November 2001

- OpenMP 3.0 for C/C++ next



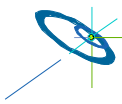
OpenMP Partners: Software Vendors

- Absoft Corporation
- Edinburgh Portable Compilers
- GENIAS Software GmbH
- KAI Software a Division of Intel America
- Myrias Computer Technologies Inc.
- The Portland Group Inc. (PGI)
- Veridian Pacific-Sierra Research



OpenMP Partners: Application Developers

- ADINA R&D Inc.
- ANSYS Inc.
- Dash Associates
- Fluent Inc.
- ILOG CPLEX Division
- Livermore Software Technology Corporation (LSTC)
- MECALOG SARL
- Oxford Molecular Group PLC
- The Numerical Algorithms Group Ltd. (NAG)



OpenMP Availability

- SGI MIPSpro F90 & F77 compilers version 7.2.1
- SGI MIPSpro C++ & C compilers version 7.3
- CRAY CF90 Programming Environment version 3.1
- CRAY C++ Programming Environment version 3.2
- KAI KAP/Pro Toolset: Guide (Fortran & C/C++)
- PGI PGF77/PGF90 Compilers (Linux, Solaris, Windows NT)
- PGI C and C++ (Linux, Solaris, Windows NT)
- DIGITAL Fortran V5.1 for Alpha/Unix
- DIGITAL C/C++ for Alpha/Unix
- NEC Fortran Compiler
- Hitachi Fortran and C Compiler
- IBM
- SUN

OpenMP Availability

	Fortran	C	C++
Compaq	✔	✔	✔
HP	✔	beta	beta
IBM	✔	✔	✔
SGI	✔	✔	✔
SUN	✔	✔	✔
Cray	✔	✔	✔
Hitachi	✔	✔	In prep
NEC	✔	In prep	In prep
Intel IA32	✔	✔	✔
Intel IA64	✔	✔	✔

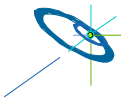
•Fortran means Fortran 90 and OpenMP 1.1

•OpenMP is available on all platforms for all language bindings

OpenMP Information

- OpenMP Homepage:
  http://www.openmp.org/
- OpenMP at HLRS:
  http://www.hlrs.de/organization/par/services/models/openmp/

- R.Chandra, L. Dagum, D. Kohr, D. Maydan, J. McDonald, R. Menon:
  Parallel programming in OpenMP.
  Academic Press, San Diego, USA, 2000, ISBN 1-55860-671-8
- R. Eigenmann, Michael J. Voss (Eds):
  OpenMP Shared Memory Parallel Programming.
  Springer LNCS 2104, Berlin, 2001, ISBN 3-540-42346-X



Outline — API

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  - Syntax
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  - Exercise and Compilation
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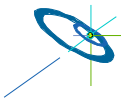
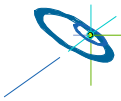


OpenMP Programming Model

- OpenMP is a shared memory model.
- Workload is distributed between threads
  - Variables can be
    - **shared among all threads**
    - **duplicated for each thread**
  - 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.
- Careless use of synchronization can lead to dead-locks



Outline — Execution Model

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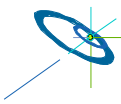
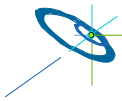
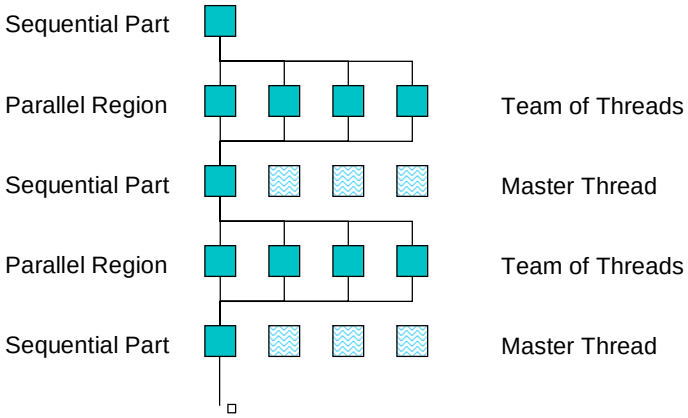


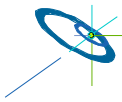
OpenMP Execution Model (1)

- Fork-join model of parallel execution
- Begin execution as a single process (master thread)
- Start of a parallel construct:
  Master thread creates team of threads
- Completion of a parallel construct:
  Threads in the team synchronize:
  implicit barrier
- Only master thread continues execution



OpenMP Execution Model (2)





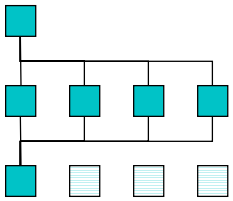
OpenMP Parallel Region Construct (1)

- Block of code to be executed by multiple threads in parallel.
  Each thread executes the **same code redundantly**!
- Fortran:
  `!$OMP PARALLEL` [*clause* [[,] *clause*] ...]
  block
  `!$OMP END PARALLEL`
  - `parallel/end parallel` directive pair must appear in the same routine
- C/C++:
  `#pragma omp parallel` [*clause* [*clause*] ...] *new-line*
  structured-block
- *clause* can be one of the following:
  - `private(`*list*`)`
  - `shared(`*list*`)`
  - ...

OpenMP Parallel Region Construct (2)

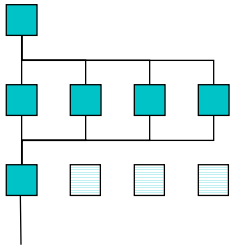
Fortran:

!$OMP PARALLEL
block
!$OMP END PARALLEL



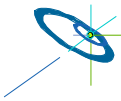
C / C++:

#pragma omp parallel
structured block
/* omp end parallel */



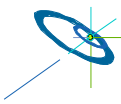
OpenMP Directive Format: Fortran

- Treated as Fortran comments
- Format:
  sentinel directive_name [*clause* [[,] *clause*] ...]
- Directive sentinels (starting at **column 1**):
  - Fixed source form: **`!$OMP`** | `C$OMP` | `*$OMP`
  - Free source form: **`!$OMP`**
- not case sensitive
- Conditional compilation
  - Fixed source form: **`!$␣`** | `C$␣` | `*$␣`
  - Free source form: **`!$␣`**
  - `#ifdef _OPENMP` **[in `my_fixed_form.F`**
    block **or `my_free_form.F90`]**
    `#endif`
  - Example:
    `!$  write(*,*) OMP_GET_NUM_PROCS(),' avail. processors'`



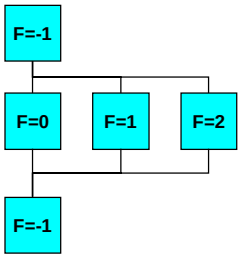
OpenMP Directive Format: C/C++

- `#pragma` directives
- Format:
  `#pragma omp` *directive_name* [*clause* [*clause*] ...] *new-line*
- Conditional compilation
  `#ifdef _OPENMP`
  block,
  e.g., `printf("%d avail.processors\n",omp_get_num_procs());`
  `#endif`
- case sensitive
- Include file for library routines:
  `#ifdef _OPENMP`
  `#include <omp.h>`
  `#endif`



OpenMP Data Scope Clauses

- `private ( list )`
  Declares the variables in *list* to be private to each thread in a team
- `shared ( list )`
  Makes variables that appear in *list* shared among all the threads in a team



- If not specified: default `shared`, but
  - stack (local) variables in called sub-programs are PRIVATE
  - Automatic variables within a block are PRIVATE
  - Loop control variable of parallel OMP
    - DO (Fortran)
    - for (C)

    is PRIVATE **[see later: Data Model]**

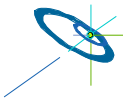
OpenMP Environment Variables

- `OMP_NUM_THREADS`
  - sets the number of threads to use during execution
  - when dynamic adjustment of the number of threads is enabled, the value of this environment variable is the maximum number of threads to use
  - `setenv OMP_NUM_THREADS 16` **[csh, tcsh]**
  - `export OMP_NUM_THREADS=16` **[sh, ksh, bash]**
- `OMP_SCHEDULE`
  - applies only to `do`/`for` and `parallel do`/`for` directives that have the schedule type `RUNTIME`
  - sets schedule type and chunk size for all such loops
  - `setenv OMP_SCHEDULE "GUIDED,4"` **[csh, tcsh]**
  - `export OMP_SCHEDULE="GUIDED,4"` **[sh, ksh, bash]**

OpenMP Runtime Library (1)

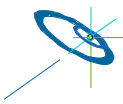
- Query functions
- Runtime functions
  - Run mode
  - Nested parallelism
- Lock functions
- C/C++: add `#include <omp.h>`
- Fortran: add all necessary OMP routine declarations, e.g.,

```
!$   INTEGER omp_get_thread_num
```



OpenMP Runtime Library (2)

- `omp_get_num_threads` Function
  Returns the number of threads currently in the team executing the parallel region from which it is called
  - Fortran:
    ```
    integer function omp_get_num_threads()
    ```
  - C/C++:
    ```
    int omp_get_num_threads(void);
    ```
- `omp_get_thread_num` Function
  Returns the thread number, within the team, that lies between `0` and `omp_get_num_threads()-1`, inclusive. The master thread of the team is thread `0`
  - Fortran:
    ```
    integer function omp_get_thread_num()
    ```
  - C/C++:
    ```
    int omp_get_thread_num(void);
    ```



Outline — Exercise 1: hello

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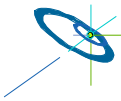
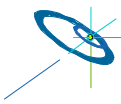


OpenMP on vision.rus....:

- Log into vision (vision.rus.uni-stuttgart.de)
- Change into directory `~/OpenMP/#NR/`
  Compile in this directory.
- Compiler calls:
  - Fortran 77/90: `f90 -mp -o` *executable source*.f / .f90 / .F / .F90
  - C: `cc -mp -o` *executable source*.c
  - C++: `CC -mp -o` executable source.cc
- Execution:
  - environment: `setenv OMP_NUM_THREADS` *number_of_threads*
  - program start: `./`*executable*



hwwsr8k: Cross Compiler Environment

- Log into hwwhpn.hww.de
- bash or tcsh [please ignore some stupid warnings]
- Change into directory `~/OpenMP/#NR/`
  Compile in this directory.
- Compiler calls: [Crosscompiler on hwwhpv]
  - Fortran 77/90: `xf90 –OSS –parallel –omp`
  - C: `xcc –O4 –pvec +Op –parallel –omp`
  - C++: `not yet available`
- Execution:
  - Log into hwwsr8k.hww.de
  - Change to `~/../hp-v/OpenMP/#NR/`
  - This is the same directory.
    If you create an executable at hwwhpv you can execute here.
  - Execute with `prun -p single ./a.out`

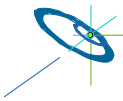
hwwsr8k: Cross Compiler Environment

- Log into hwwhpn.hww.de
- bash
- Change into directory `~/OpenMP/#NR/`
  Compile in this directory.
- Compiler calls for development: [Crosscompiler on hwwhpv]
  - Fortran 77/90: `xf90 -omp -procnum=N`
  - C: `xcc -omp -parallel=1 -O2`
  - C++: `not yet available`
- Compiler calls for production: [Crosscompiler on hwwhpv]
  - Fortran 77/90: `xf90 –OSS –parallel –omp`
  - C: `xcc –O4 –pvec (+Op) –parallel –omp`
  - C++: `not yet available`
- Execution:
  - Log into hwwsr8k.hww.de
  - Change to `~/OpenMP/#NR/`
  - This is the same directory.
    If you create an executable at hwwhpv you can execute here.
  - Execute with `prun -p single ./a.out`

hwwsx*: Cross Compiler Environment

- Log into hwwhpn.hww.de
- Change into directory `~/OpenMP/#NR/`
  Compile in this directory.
- Compiler calls: [Crosscompiler on hwwhpn]
  - Fortran 77/90: `sxf90 [-sx4] -P openmp`
  - C: `available with C++`
  - C++: `available soon`
- Log into hwwsx2.hww.de
  Change to `~/hpv/OpenMP/#NR/`
  This is the same directory.
  If you create an executable at hwwhpn you can execute here.

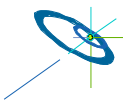
- Don't forget -sx4 compiler flag to create executables for sx4!



OpenMP Exercise 1: Hello World Program (1)

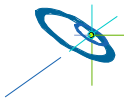
- Goal: usage of
  - runtime library calls
  - conditional compilation
  - environment variables
  - parallel regions, `private` and `shared` clauses

- Working directory: `~/OpenMP/#NR/hello/`
  `#NR` = number of your PC, e.g., 07
- Serial programs:
  - Fortran 77: `hello.f`
  - Fortran 90: `hello.f90`
  - C: `hello.c`



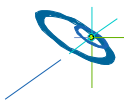
OpenMP Exercise 1: Hello World Program (2)

- compile **serial** program `hello.[f|f90|c]` and run
- add call to `omp_get_thread_num()` in `hello.[f|f90|c]` and assign function result to variable `i`, and do this with conditional compilation (`!$` in Fortran, `#ifdef _OPENMP` in C)
- compile **serially** and run
  - expected result: one line with `i=-1`
- compile **as OpenMP** program and run
  - add OpenMP compile option, e.g., `-mp` on SGI
  - expected result: one line with `i=0`
- set environment variable `OMP_NUM_THREADS` to 2 and run
  - expected result: one line with `i=0`
  - Why?
- value of i? number of printed lines?



OpenMP Exercise 1: Hello World Program (3)

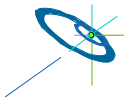
- add parallel region in `hello.[f|f90|c]`, compile and run
  - value of i? number of printed lines?
  - expected results: two lines, but values may be 0&0, 0&1, 1&0 or 1&1
- change `OMP_NUM_THREADS` to 4 and run
  - value of i? number of printed lines?
  - expected results: four lines, but also unpredictable
- add `PRIVATE(i)` clause in `hello.[f|f90|c]`, compile and run
  - value of i? number of printed lines?
  - expected results: four lines with `i`=0, 1, 2, and 3 in some order
- change `OMP_NUM_THREADS` and run
  - value of i? number of printed lines?
- compile again **serially** and run
  - expected result: one line with `i=-1`



OpenMP Exercise 1: Hello World Program - Solution

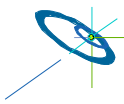
`Location: ~/OpenMP/Aufgabe/solution/hello`

- `hello1.[f|f90|c]`: original program
- `hello2.[f|f90|c]`: incorrect (without parallel region) !!!
- `hello3.[f|f90|c]`: incorrect (`i` is not private) !!!
- `hello4.[f|f90|c]`: solution □



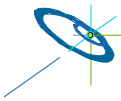
OpenMP Exercise 1: Hello World Program - Summary

- Conditional compilation allows to keep the serial version of the program in the same source files
- compilers need to be used with `special` option for OpenMP directives to take any effect
- Parallel regions are executed by each thread in the same way unless worksharing directives are used
- Decision about `private` or `shared` status of variables is important



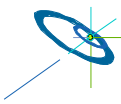
Outline — Work-sharing directives

- Standardization Body
- OpenMP Application Program Interface (API)
- Execution Model
  - Parallel regions: team of threads
  - Syntax
  - Data environment (part 1)
  - Environment variables
  - Runtime library routines
  - Exercise and Compilation
- **Work-sharing directives**
  - **Which thread executes which statement or operation?**
  - **Synchronization constructs, e.g., critical sections**
  - **Nesting and Binding**
  - **Exercise 2: pi**
- Data environment and combined constructs
  - Private and shared variables
  - Combined parallel work-sharing directives
- Summary of OpenMP API
- OpenMP Pitfalls



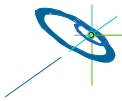
Work-sharing and Synchronization

- Which thread executes which statement or operation?
- and when?
  - Work-sharing constructs
  - Master and synchronization constructs
- **i.e., organization of the parallel work!!!**



OpenMP Work-sharing Constructs

- Divide the execution of the enclosed code region among the members of the team
- Must be enclosed dynamically within a parallel region
- They do not launch new threads
- No implied barrier on entry
- `sections` directive
- `do` directive (Fortran)
- `for` directive (C/C++)



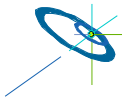
OpenMP `sections` Directives (1)

- Several *blocks* are executed in parallel
- Fortran:

```
!$OMP SECTIONS [ clause [ [ , ] clause ] ... ]
[!$OMP SECTION ]
   block1
[!$OMP SECTION
   block2 ]
  ...
!$OMP END SECTIONS [nowait]
```

- C/C++:

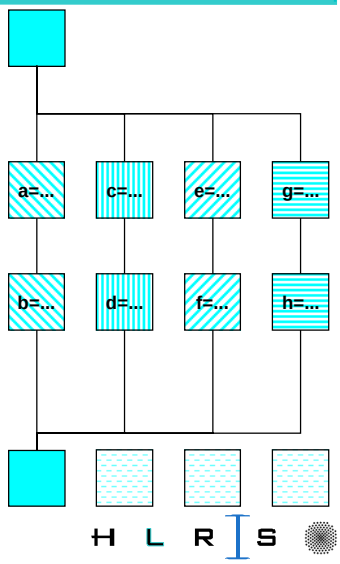
```
#pragma omp sections [ clause [ clause ] ... ] new-line
  {
    [#pragma omp section new-line ]
       structured-block1
    [#pragma omp section new-line
       structured-block2 ]
     ...
  }
```



OpenMP sections Directives (2)

Fortran:

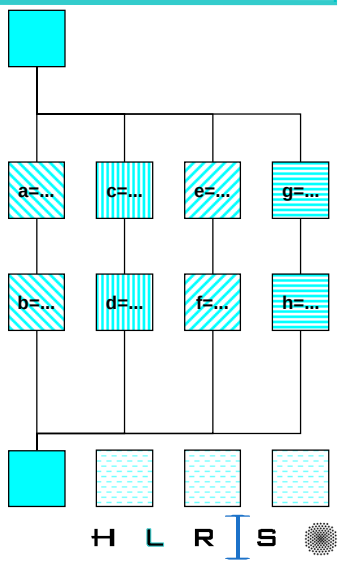
```
!$OMP PARALLEL
!$OMP SECTIONS
      a=...
      b=...
!$OMP SECTION
      c=...
      d=...
!$OMP SECTION
      e=...
      f=...
!$OMP SECTION
      g=...
      h=...
!$OMP END SECTIONS
!$OMP END PARALLEL
```



OpenMP sections Directives (3)

C / C++:

```
#pragma omp parallel
{
#pragma omp sections
  {{  a=...;
      b=...; }
#pragma omp section
    {  c=...;
       d=...; }
#pragma omp section
    {  e=...;
       f=...; }
#pragma omp section
    {  g=...;
       h=...; }
  } /*omp end sections*/
} /*omp end parallel*/
```



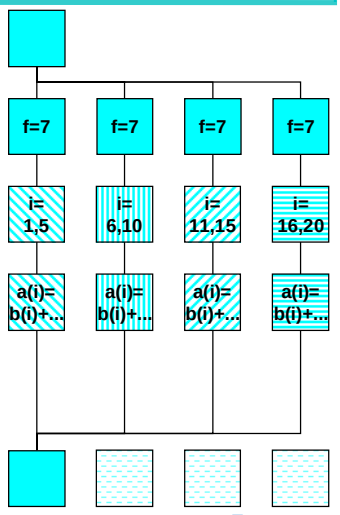
OpenMP do/for Directives (1)

- Immediately following loop executed in parallel
- Fortran:
  `!$OMP do` [*clause* [[,] *clause*] ...]
  do_loop
  [`!$OMP end do` [`nowait`]]
- If used, the `end do` directive must appear immediately after the end of the loop
- C/C++:
  `#pragma omp for` [*clause* [*clause*] ...] *new-line*
  for-loop
- The corresponding `for` loop must have *canonical shape*

OpenMP do/for Directives (2)

Fortran:

```
!$OMP PARALLEL private(f)
    f=7
!$OMP DO
    do i=1,20
      a(i) = b(i) + f * i
    end do
!$OMP END DO
!$OMP END PARALLEL
```



OpenMP do/for Directives (3)

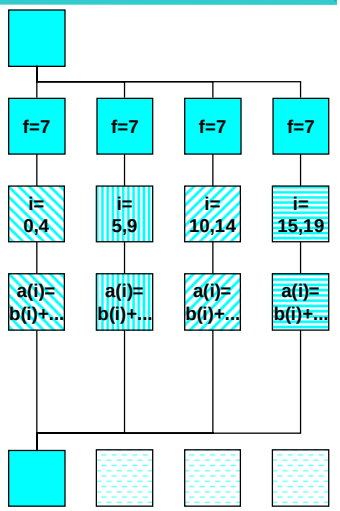
C / C++:

```
#pragma omp parallel private(f)
{
      f=7;

#pragma omp for
      for (i=0; i<20; i++)
         a[i] = b[i] + f * (i+1);



} /* omp end parallel */
```



OpenMP do/for Directives (4)

- *clause* can be one of the following:
  - `private(`*list*`)` **[see later: Data Model]**
  - `reduction(`*operator*`:` *list*`)` **[see later: Data Model]**
  - `schedule(` *type*`[ ,` *chunk*`] )`
  - `nowait` (C/C++: on `#pragma omp for`) (Fortran: on `$!OMP END DO`)
  - ...
- Implicit barrier at the end of do/`for` unless `nowait` is specified
- If `nowait` is specified, threads do not synchronize at the end of the parallel loop
- `schedule` clause specifies how iterations of the loop are divided among the threads of the team.
  - Default is implementation dependent

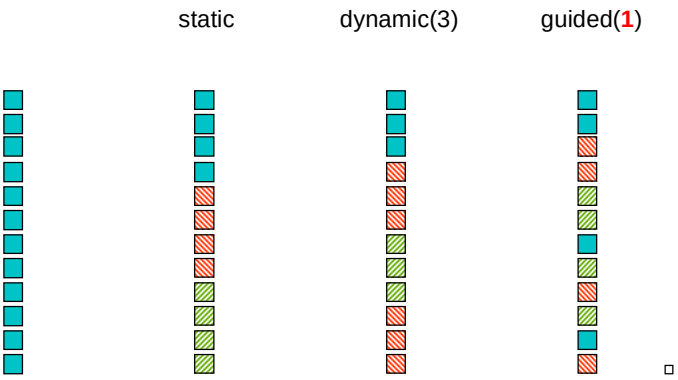
OpenMP schedule Clause

Within `schedule( type [ , chunk ] )` *type* can be one of the following:

- `static`: Iterations are divided into pieces of a size specified by *chunk*. The pieces are statically assigned to threads in the team in a round-robin fashion in the order of the thread number.
  Default chunk size: one contiguous piece for each thread.
- `dynamic`: Iterations are broken into pieces of a size specified by *chunk*. As each thread finishes a piece of the iteration space, it dynamically obtains the next set of iterations. Default chunk size: 1.
- `guided`: The chunk size is reduced in an exponentially decreasing manner with each dispatched piece of the iteration space.
  chunk specifies the smallest piece (except possibly the last).
  Default chunk size: 1. Initial chunk size is implementation dependent.
- `runtime`: The decision regarding scheduling is deferred until run time. The schedule type and chunk size can be chosen at run time by setting the `OMP_SCHEDULE` environment variable.

Default schedule: implementation dependent.□

Loop scheduling



Outline — Synchronization constructs

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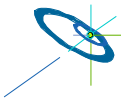
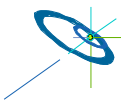


OpenMP Synchronization

- Implicit Barrier
  - beginning and end of `parallel` constructs
  - end of all other control constructs
  - implicit synchronization can be removed with **`nowait`** clause
- Explicit
  - `critical`
  - ...



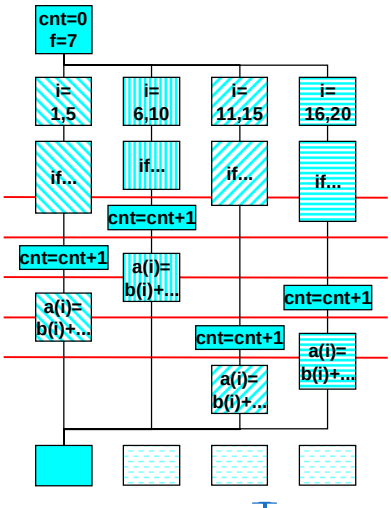
OpenMP `critical` Directive

- Enclosed code
  - executed by all threads, but
  - **restricted to only one thread at a time**
- Fortran:
  `!$OMP CRITICAL [ ( name ) ]`
  block
  `!$OMP END CRITICAL [ ( name ) ]`
- C/C++:
  `#pragma omp critical [ ( name ) ]` *new-line*
  structured-block
- A thread waits at the beginning of a critical region until no other thread in the team is executing a critical region with the same name. All unnamed `critical` directives map to the same unspecified name.

OpenMP `critical` — an example (Fortran)

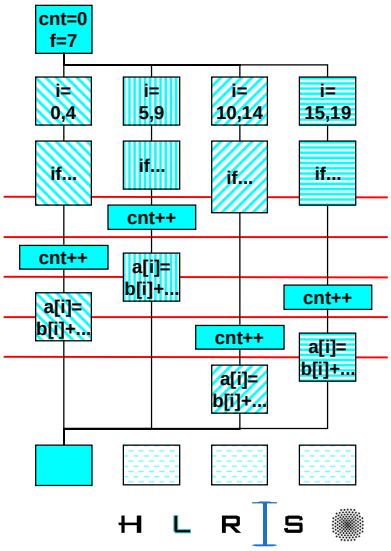
Fortran:

```
cnt = 0
f=7
!$OMP PARALLEL
!$OMP DO
do i=1,20
  if (b(i).eq.0) then
!$OMP CRITICAL
    cnt = cnt+1
!$OMP END CRITICAL
  endif
  a(i) = b(i) + f * i
end do
!$OMP DO
!$OMP END PARALLEL
```



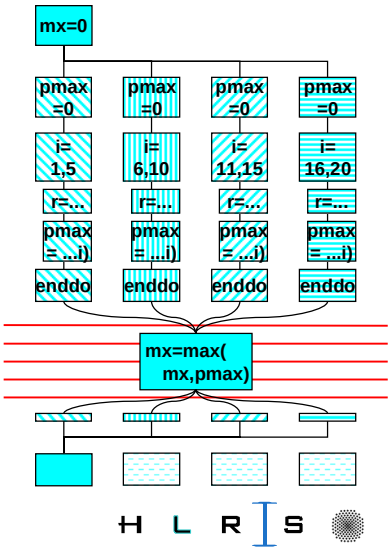
OpenMP `critical` — an example (C/C++)

```
C / C++:   cnt = 0;
           f=7;
      #pragma omp parallel
      {
      #pragma omp for
           for (i=0; i<20; i++) {
              if (b[i] == 0) {
                 #pragma omp critical
                  cnt ++;
              } /* endif */
              a[i] = b[i] + f * (i+1);
           } /* end for */
      } /*omp end parallel */
```



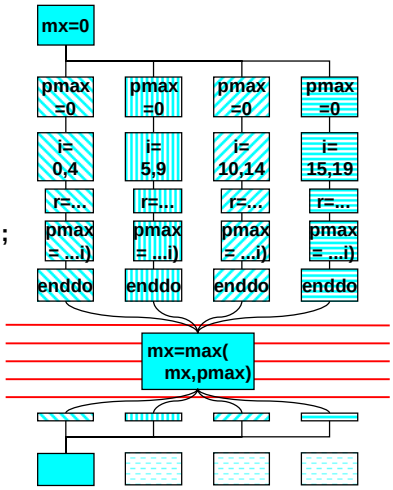
OpenMP `critical` — another example (Fortran)

```
      mx = 0
!$OMP PARALLEL private(pmax)
      pmax = 0
!$OMP DO private(r)
      do i=1,20
         r = work(i)
         pmax = max(pmax,r)
      end do
!$OMP END DO
!$OMP CRITICAL
      mx = max(mx,pmax)
!$OMP END CRITICAL
!$OMP END PARALLEL
```



OpenMP `critical` — another example (C/C++)

```
      mx = 0;
#pragma omp parallel private(pmax)
{     pmax = 0;
      #pragma omp for private(r)
      for (i=0; i<20; i++)
      {   r = work(i);
          pmax = (r>pmax ? r : pmax);
      } /*end for*/
      /*omp end for*/
      #pragma omp critical
      mx= (pmax>mx ? pmax : mx);
      /*omp end critical*/
} /*omp end parallel*/
```



Outline — Nesting and Binding

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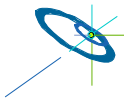
OpenMP Vocabulary

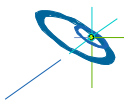
- **Static extent** of the parallel construct:
  statements enclosed lexically within the construct
- **Dynamic extent** of the parallel construct:
  further includes the routines called from within the construct
- **Orphaned Directives**:
  Do not appear in the lexical extent of the parallel construct but lie in the dynamic extent
  - Parallel constructs at the top level of the program call tree
  - Directives in any of the called routines



OpenMP Vocabulary

```
      program a                    subroutine b
!$OMP PARALLEL                !$OMP DO
      call b                       do i=1,n
      call c                       ...
!$OMP END PARALLEL                 enddo
      call d                   !$OMP END DO
      stop                         return
      end                          end
                                   subroutine c
                                   return
                                   end
```

Static Extent Dynamic Extent Orphaned Directives



OpenMP Control Structures — Summary

- Parallel region construct
  - `parallel`
- Work-sharing constructs
  - `sections`
  - `do` (Fortran)
  - `for` (C/C++)
- Combined parallel work-sharing constructs **[see later]**
  - `parallel do` (Fortran)
  - `parallel for` (C/C++)
- Synchronization constructs
  - `critical` □

Outline — Exercise 2: pi

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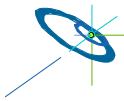
  - Exercise and Compilation
- **Work-sharing directives**
  - **Which thread executes which statement or operation?**
  - **Synchronization constructs, e.g., critical sections**
  - **Nesting and Binding**
  - **Exercise 2: pi**
- Data environment and combined constructs
  - Private and shared variables
  - Combined parallel work-sharing directives
- Summary of OpenMP API
- OpenMP Pitfalls

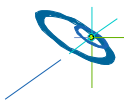
OpenMP Exercise 2: pi Program (1)

- Goal: usage of
  - work-sharing constructs: `do`/`for`
  - `critical` directive
- Working directory: `~/OpenMP/#NR/pi/`
  `#NR` = number of your PC, e.g., 07
- Serial programs:
  - Fortran 77: `pi.f` and `scdiff.f90`
  - Fortran 90: `pi.f90` and `scdiff.f90`
  - C: `pi.c`



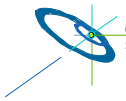
OpenMP Exercise 2: pi Program (2)

- compile serial program `pi.[f|f90|c]` and run
- add parallel region and `do`/`for` directive in `pi.[f|f90|c]` and compile
- set environment variable `OMP_NUM_THREADS` to 2 and run
  - value of pi? (should be wrong!)
- run again
  - value of pi? (...wrong and unpredictable)
- set environment variable `OMP_NUM_THREADS` to 4 and run
  - value of pi? (...and stays wrong)
- run again
  - value of pi? (...but where s the race-condition?)



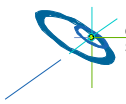
OpenMP Exercise 2: pi Program (3)

- add `private(x)` clause in `pi.[f|f90|c]`and compile
- set environment variable `OMP_NUM_THREADS` to 2 and run
  - value of pi? (shoud be still incorrect ...)
- run again
  - value of pi?
- set environment variable `OMP_NUM_THREADS` to 4 and run
  - value of pi?
- run again
  - value of pi? (... and where is the second race-condition?)



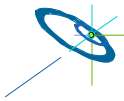
OpenMP Exercise 2: pi Program (4)

- add `critical` directive in `pi.[f|f90|c]` around the sum-statement and **don't** compile
- reduce the number of iterations to 1,000,000 and compile
- set environment variable `OMP_NUM_THREADS` to 2 and run
  - value of pi? (should be now correct!, but huge CPU time!)
- run again
  - value of pi? (but not reproducble iin the last bit!)
- set environment variable `OMP_NUM_THREADS` to 4 and run
  - value of pi? execution time? (Oh, takes iit longer?)
- run again
  - value of pi? execution time?
  - How can you optimize your code?



OpenMP Exercise 2: pi Program (5)

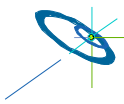
- move `critical` directive in `pi.[f|f90|c]` outside loop, restore old iteration length (10,000,000) and compile
- set environment variable `OMP_NUM_THREADS` to 2 and run
  - value of pi?
- run again
  - value of pi?
- set environment variable `OMP_NUM_THREADS` to 4 and run
  - value of pi? execution time? (correct pi, half execution time)
- run again
  - value of pi? execution time?



OpenMP Exercise 2: pi Program - Solution

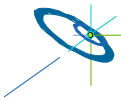
`Location: ~/OpenMP/Aufgabe/solution/pi`

- `pi.[f|f90|c]`: original program
- `pi1.[f|f90|c]`: incorrect (no private, no synchronous global access) !!!
- `pi2.[f|f90|c]`: incorrect (still no synchronous global access to `sum`) !!!
- `pic.[f|f90|c]`: solution with `critical` directive, but extremely slow!
- `pic2.[f|f90|c]`: solution with `critical` directive outside loop □



Outline — Date environment and combined constructs

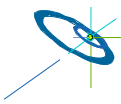
- Standardization Body
- OpenMP Application Program Interface (API)
- Execution Model
  - Parallel regions: team of threads
  - Syntax
  - Data environment (part 1)
  - Environment variables
  - Runtime library routines
- Work-sharing directives
  - Which thread executes which statement or operation?
  - Synchronization constructs, e.g., critical sections
  - Nesting and Binding
- **Data environment and combined constructs**
  - **Private and shared variables**
  - **Reduction clause**
  - **Combined parallel work-sharing directives**
  - **Exercise 3: pi**
- Summary of OpenMP API
- OpenMP Pitfalls



OpenMP Data Scope Clauses

- `private ( list )`
  Declares the variables in *list* to be private to each thread in a team
- `shared ( list )`
  Makes variables that appear in *list* shared among all the threads in a team
- If not specified: default `shared, but`
  - stack (local) variables in called subroutines are PRIVATE
  - Automatic variables within a block are PRIVATE
  - Loop control variable of parallel OMP
    - DO (Fortran)
    - FOR (C)

    is PRIVATE □



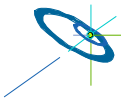
Private Clause

- `Private (variable)` creates a local copy of variable for each thread
  - value is unitialized
  - private copy is not storage associated with the original

```
      program wrong
      JLAST = -777
!$OMP PARALLEL DO PRIVATE(JLAST)
      DO J=1,1000
           ...
           JLAST = J
      END DO
!$OMP END PARALLEL DO
      print *, JLAST
```

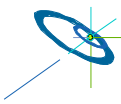
—> writes -777 !!!

- If initialization is necessary use `FIRSTPRIVATE( var )`
- If value is needed after loop use `LASTPRIVATE( var )`
  —> `var` is updated by the thread that computes
  - the sequentially last iteration (on `do` or `for` loops)
  - the last section



OpenMP `reduction` Clause

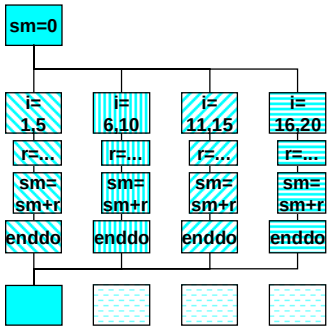
- `reduction` (*operator*: *list*)
- Performs a reduction on the variables that appear in *list*, with the operator *operator*
- *operator*: one of
  - Fortran:
    `+`, `*`, `-`, `.and.`, `.or.`, `.eqv.`, `.neqv.` or
    `max`, `min`, `iand`, `ior`, or `ieor`
  - C/C++:
    `+`, `*`, `-`, `&`, `^`, `|`, `&&`, or `||`
- Variables must be `shared` in the enclosing context
- At the end of the `reduction`, the shared variable is updated to reflect the result of combining the original value of the shared reduction variable with the final value of each of the private copies using the operator specified □



OpenMP `reduction` — an example (Fortran)

Fortran:

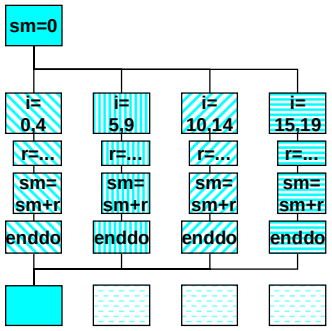
```
      sm = 0
!$OMP PARALLEL DO private(r),
                  reduction(+:sm)
      do i=1,20
         r = work(i)
         sm = sm + r
      end do
!$OMP END PARALLEL DO
```



OpenMP `reduction` — an example (C/C++)

C / C++:

```
      sm = 0;
#pragma parallel for private(r)
                     reduction(+:sm)
      for( i=0; i<20; i++)
      {   r = work(i);
          sm = sm + r ;
      } /*end for*/
/*omp end parallel for*/
```



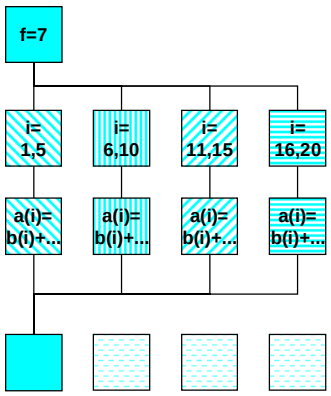
OpenMP Combined `parallel do/for` Directive

- Shortcut form for specifying a parallel region that contains a single `do/for` directive
- Fortran:
  `!$OMP PARALLEL DO` [*clause* [[,] *clause*] ...]
  do_loop
  [`!$OMP END PARALLEL DO`]
- C/C++:
  `#pragma omp parallel for` [*clause* [*clause*] ...] *new-line*
  for-loop
- This directive admits all the clauses of the `parallel` directive and the `do/for` directive except the `nowait` clause, with identical meanings and restrictions

OpenMP Combined `parallel do/for` — an example (Fortran)

Fortran:

```
      f=7
!$OMP PARALLEL DO
      do i=1,20
        a(i) = b(i) + f * i
      end do
!$OMP END PARALLEL DO
```

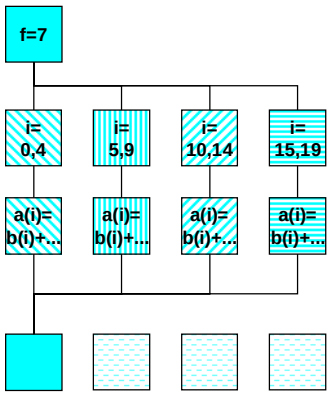


OpenMP Combined `parallel do/for` — an example (C/C++)

C / C++:

```
f=7;

#pragma omp parallel for
    for (i=0; i<20; i++)
      a[i] = b[i] + f * (i+1);
```



Outline — Exercise 3: pi with reduction

OpenMP Exercise 3: pi Program (6)

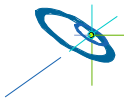
- Goal: usage of
  - work-sharing constructs: do/`for`
  - `critical` directive
  - `reduction` clause
  - combined parallel work-sharing constructs: `parallel do`/`parallel for`
- Working directory: `~/OpenMP/#NR/pi/`
  `#NR` = number of your PC, e.g., 07
- Use your result `pi.[f|f90|c]` from the exercise 2
- or copy solution of exercise 2 to your directory:
  - `cp ~/OpenMP/Aufgabe/solution/pi/pic2.* .`

OpenMP Exercise 3: pi Program (7)

- remove `critical` directive in `pi.[f|f90|c]`, add `reduction` clause and compile
- set environment variable `OMP_NUM_THREADS` to 2 and run
  - value of pi?
- run again
  - value of pi?
- set environment variable `OMP_NUM_THREADS` to 4 and run
  - value of pi? execution time?
- run again
  - value of pi? execution time?

OpenMP Exercise 3: pi Program (8)

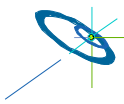
- change parallel region + `do`/`for` to the combined parallel work-sharing construct `parallel do`/`parallel for` and compile
- set environment variable `OMP_NUM_THREADS` to 2 and run
  - value of pi?
- run again
  - value of pi?
- set environment variable `OMP_NUM_THREADS` to 4 and run
  - value of pi?
- run again
  - value of pi?



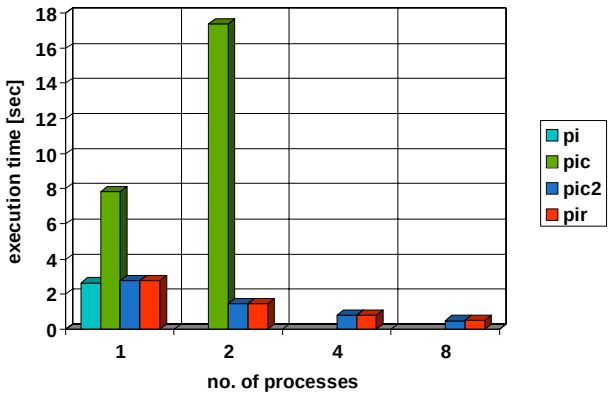
OpenMP Exercise 3: pi Program - Solution

`Location: ~/OpenMP/Aufgabe/solution/pi`

- `pi.[f|f90|c]`: original program
- `pi1.[f|f90|c]`: incorrect (no private, no synchronous global access) !!!
- `pi2.[f|f90|c]`: incorrect (still no synchronous global access to `sum`) !!!
- `pic.[f|f90|c]`: solution with `critical` directive, but extremely slow!
- `pic2.[f|f90|c]`: solution with `critical` directive outside loop
- `pir.[f|f90|c]`: solution with `reduction` clause □



OpenMP Exercise 3: pi Program - Execution Times F90



OpenMP Exercise 3: pi Program - Summary

- Decision about `private` or `shared` status of variables is important
- In Fortran correct results with `reduction` clause and with `critical` directive
- Using the simple version of the `critical` directive is much more time consuming than using the `reduction` clause ⇒ no parallelism left
- More sophisticated use of `critical` directive leads to much better performance in Fortran;
- Convenient `reduction` clause
- Convenient shortcut form

Outline — Summary of the OpenMP API

- Standardization Body
- OpenMP Application Program Interface (API)
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  - Parallel regions: team of threads
  - Syntax
  - Data environment (part 1)
  - Environment variables
  - Runtime library routines
- Work-sharing directives
  - Which thread executes which statement or operation?
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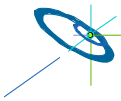
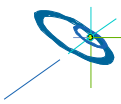
  - Exercise 3: pi
- **Summary of OpenMP API**
- OpenMP Pitfalls

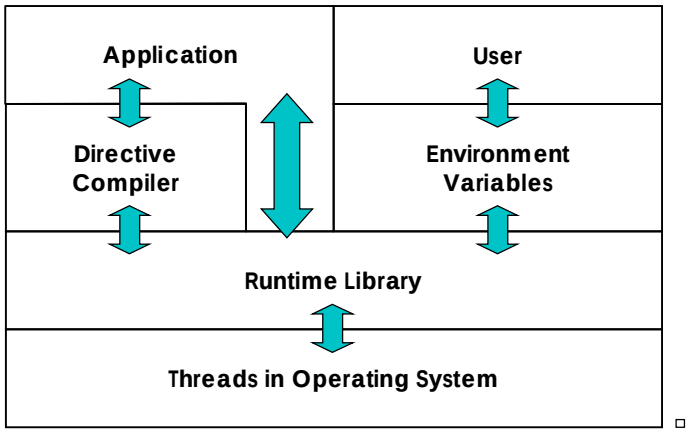


OpenMP Components

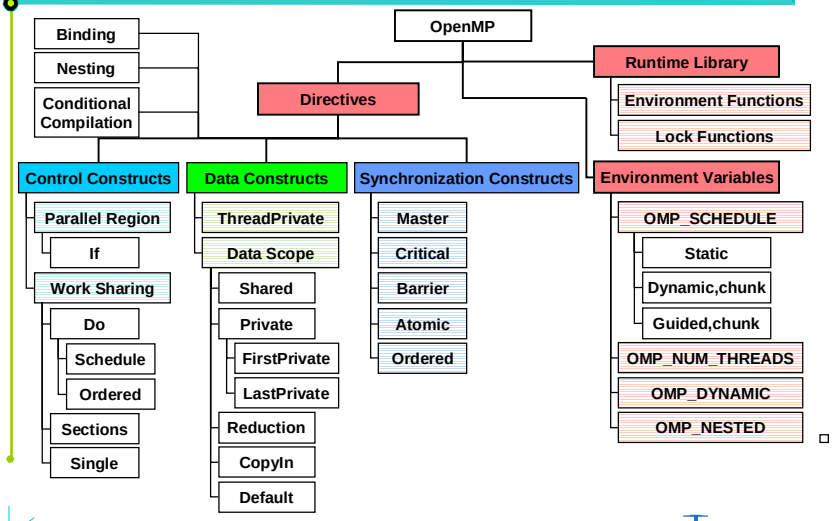
- Set of compiler directives
  - Control Constructs
    - **Parallel Regions**
    - **Work-sharing constructs**
  - Data environment
  - Synchronization
- Runtime library functions
- Environment variables



OpenMP Architecture



OpenMP Constructs



Outline — OpenMP Pitfalls

- Standardization Body
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- Summary of OpenMP API
- **OpenMP Pitfalls**

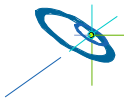
Two types of SMP errors

- Race Conditions
  - Def.: *Two threads access the same shared variable **and** at least one thread modifies the variable **and** the sequence of the accesses is undefined, i.e. unsynchronized*
  - The outcome of a program depends on the detailed timing of the threads in the team.
  - This is often caused by unintended share of data
- Deadlock
  - Threads lock up waiting on a locked resource that will never become free.
    - **Avoid lock functions if possible**
    - **At least avoid nesting different locks**

Example for race condition (1)

```
!$OMP PARALLEL SECTIONS
       A = B + C
!$OMP SECTION
       B = A + C
!$OMP SECTION
       C = B + A
!$OMP END PARALLEL SECTIONS
```

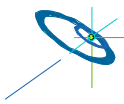
- The result varies unpredictably based on specific order of execution for each section.
- Wrong answers produced without warning!



Example for race condition (2)

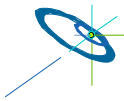
```
!$OMP PARALLEL SHARED (X), PRIVATE(TMP)
       ID = OMP_GET_THREAD_NUM()
!$OMP DO REDUCTION(+:X)
       DO 100 I=1,100
              TMP = WORK1(I)
              X = X + TMP
100  CONTINUE
!$OMP END DO NOWAIT
       Y(ID) = WORK2(X,ID)
!$OMP END PARALLEL
```

- The result varies unpredictably because the value of X isn't dependable until the barrier at the end of the do loop.
- Solution: Be careful when you use **NOWAIT**.



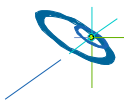
OpenMP programming recommendations

- Solution 1:
  Analyze your code to make sure every semantically permitted interleaving of the threads yields the correct results.
- Solution 2:
  Write SMP code that is portable and equivalent to the sequential form.
  - Use a safe subset of OpenMP.
  - Follow a set of “rules” for Sequential Equivalence.



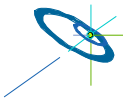
Sequential Equivalence

- Two forms of sequential equivalence
  - Strong SE: bitwise identical results.
  - Weak SE: equivalent mathematically but due to quirks of floating point arithmetic, not bitwise identical.
- Using a limited subset of OpenMP and a set of rules allows to program this way
- Advantages:
  - program can be tested,debugged and used in sequential mode
  - this style of programming is also less error prone



Rules for Strong Sequential Equivalence

- Control data scope with the base language
  - Avoid the data scope clauses.
  - Only use private for scratch variables local to a block (eg. temporaries or loop control variables) whose global initialization don't matter.
- Locate all cases where a shared variable can be written by multiple threads.
  - The access to the variable must be protected.
  - If multiple threads combine results into a single value, enforce sequential order.
  - Do not use the reduction clause carelessly. (no floating point operations (+,-,*)
  - **Use the ordered directive and the ordered clause.**
- Concentrate on loop parallelism/data parallelism



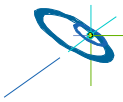
Example for Ordered Clause: pio.c

```
#pragma omp for ordered
 for (i=1;i<=n;i++)
 {
   x=w*((double)i-0.5);
   myf=f(x);      /* f(x) should be expensive! */
#pragma omp ordered
   {
    sum=sum+myf;
   }
 }
```

ordered clause

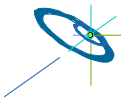
ordered directive

- "ordered" corresponds to "critical" + "order of execution"
- only efficient if workload outside ordered directive is large enough



Rules for weak sequential equivalence

- For weak sequential equivalence only mathematically valid constraints are enforced.
  - **Floating point arithmetic is not associative and not commutative.**
  - **In many cases, no particular grouping of floating point operations is mathematically preferred so why take a performance hit by forcing the sequential order?**
  - In most cases, if you need a particular grouping of floating point operations, you have a bad algorithm.
- How do you write a program that is portable and satisfies weak sequential equivalence?
  - Follow the same rules as the strong case, but relax sequential ordering constraints.

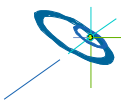


Optimization Problems

- Prevent frequent synchronizations, e.g., with critical sections

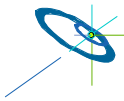
```
max = 0;
#pragma omp parallel private(partial_max)
{
   partial_max = 0;
#pragma omp for
   for (i=0; i<10000; i++)
   {
     x[i] = ...;
     if (x[i] > partial_max) partial_max = x[i];
   }
#pragma omp critical
   if (partial_max > max) max = partial_max;
}
```

- Loop: **`partial_max`** is updated locally up to **`10000/#threads`** times
- Critical section: **`max`** is updated only up to **`#threads`** times



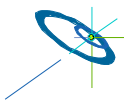
OpenMP Summary

- Standardized compiler directives for shared memory programming
- Fork-join model
- Support from all relevant hardware vendors
- OpenMP offers an incremental approach to parallelism
- Equivalence to sequential program is possible if necessary
  - strong equivalence
  - weak equivalence
  - no equivalence
- OpenMP programming includes race conditions and deadlocks, but a subset of OpenMP can be considered safe
- Optimization: prevent frequent synchronizations



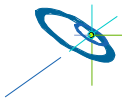
OpenMP
Exercise Heat Conduction

Isabel Loebich
loebich@hlrs.de



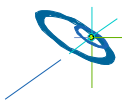
OpenMP Exercise: Heat Conduction(1)

- solves the PDE for unsteady heat conduction $df/dt=\Delta f$
- uses an explicit scheme: forward-time, centered-space
- solves the equation over a unit square domain
- initial conditions: *f=0* everywhere inside the square
- boundary conditions: *f=x* on all edges
- number of grid points in each direction: 80



OpenMP Exercise: Heat Conduction (2)

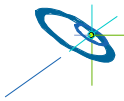
- Goals:
  - parallelization of a real application
  - usage of different parallelization methods with respect to their effect on execution times
- Working directory: `~/OpenMP/#NR/heat/`
  `#NR` = number of your PC, e.g., 07
- Serial programs:
  - Fortran 77: `heat.f` and `scdiff.f90`
  - Fortran 90: `heat.f90` and `scdiff.f90`
  - C: `heat.c`
- Compiler calls:
  - Fortran 77/90: sxf90 -sx4/-sx5
  - C: `not yet available for OpenMP`



OpenMP Exercise: Heat Conduction (3)

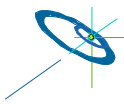
3 versions provided:

- small version, for verifying purposes: `heat.[f|f90|c]`
  - 20 x 11 grid points, max 20000 iterations
  - prints array values before and after iteration loop
- big version: `heat-big.[f|f90|c]`
  - 80 x 80 grid points, max 20000 iterations
  - doesn‘t print array values
- version for use with compiler switch -O3: `heat-opt.[f|f90|c]`
  - 150 x 150 grid points, max 50000 iterations
  - doesn‘t print array values □



OpenMP Exercise: Heat Conduction (4)

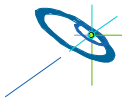
- parallelize small version using different methods and check results
  - `critical` directive
  - `reduction` clause
  - parallel region + work-sharing constructs
  - combined parallel work-sharing construct
- select one method and parallelize big version
- watch execution times
- use SCHEDULE clause with different values for `type` and `chunk` and watch effects on execution times
- optional: also parallelize version for use with compiler option -O3



OpenMP Exercise: Heat - Solution C/F77/F90 (1)

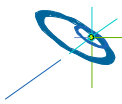
`Location: ~/OpenMP/Aufgabe/solution/hello`

- `heat.[f|f90|c]`: original program
- `heatc.[f|f90|c]`: solution with `critical` directive, one parallel region inside iteration loop
- `heatc2.[f|f90|c]`: solution with `critical` directive outside inner loop, one parallel region inside iteration loop
- `heatr.[f|f90|c]`: solution with `reduction` clause, one parallel region inside iteration loop
- `heatp.[f|f90|c]`: solution with `reduction` clause, two combined `parallel do`s inside iteration loop
- `heats.[f|f90|c]`: same as `heatr.[f|f90|c]`, `schedule(runtime)` clause added
- `heat?-big.[f|f90|c]` and `heat?-opt.[f|f90|c]`: corresponding versions with 80 x 80 grid and 150 x 150 grid, for use with -O3 compiler switch □

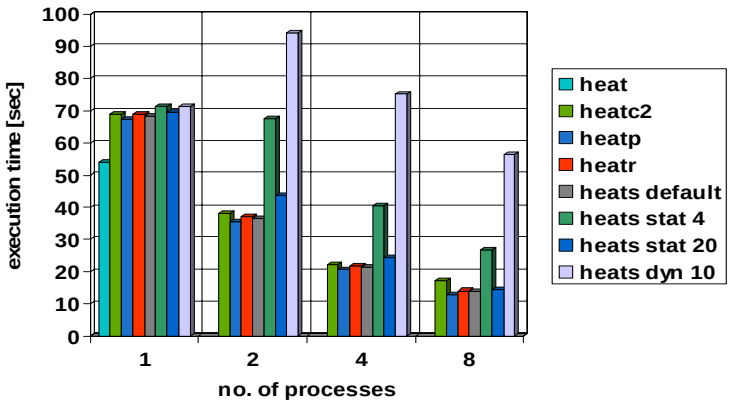


OpenMP Exercise: Heat - Solution C/F77/F90 (2)

- As we already learned `heatc` does not use parallelism very well
- Better: `heatc2`
- Overhead for creating two parallel regions in version `heatp` expected
- There should be no execution time differences between versions `heatr` and `heats` with default schedule
- Different execution times for different `schedule` schemes expected
- Version `big`: 14320 iterations
- Version `opt`: 44616 iterations



OpenMP Exercise: Heat - Execution Times F90/opt



OpenMP Exercise: Heat Conduction - Summary

- Overhead for parallel versions using 1 thread
- Be careful when using other than default scheduling strategies:
  - `dynamic` is generally expensive
  - `static`: overhead for small chunk sizes is clearly visible