Shared Memory Parallel Programming with OpenMP

Overview and Introduction

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Are Choice of Hardware and Choice of Programming Languages connected?

Yes!

This is e.g. due to different storing philosophy of matrices.

- FORTRAN stores matrices in column-major format,
- most other languages use row-major.

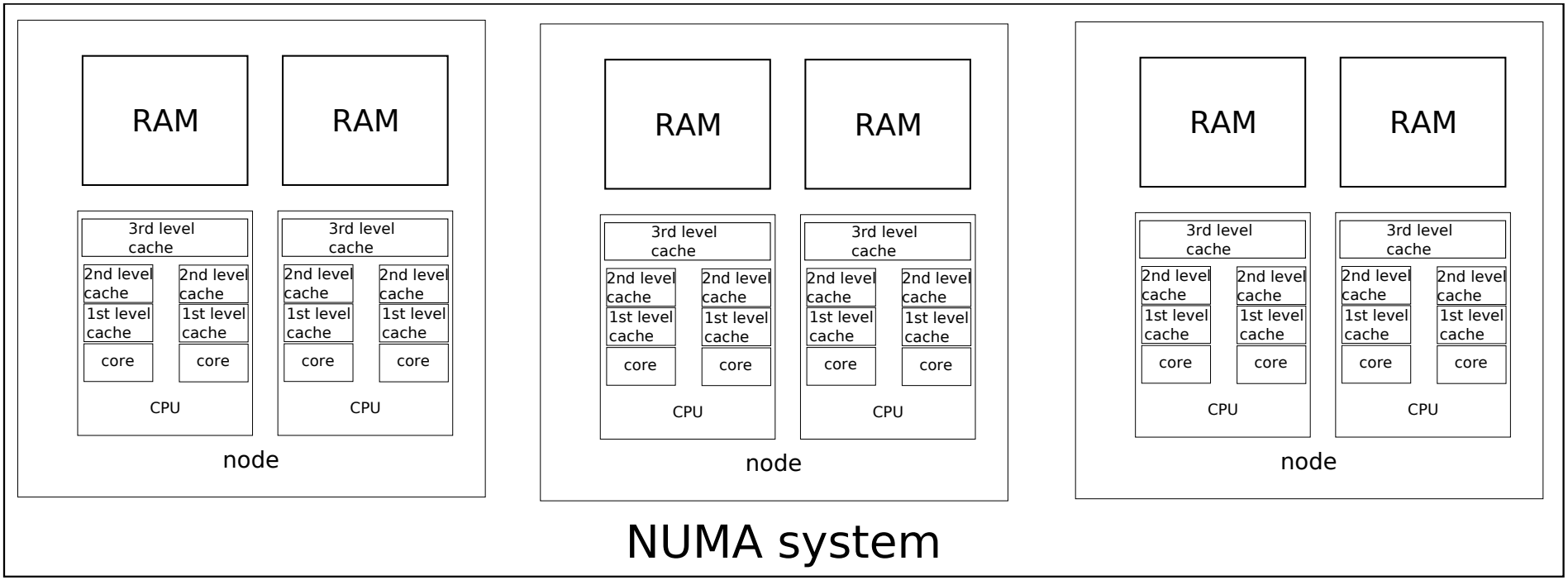
The column-major format is especially suited for vectorizing code and matrix-vector multiplications on vector-processors.

Other factors include

- available libraries
- extensions (OpenCL, OpenMP, MPI) are only available for some languages
  notably
  - OpenMP for C/C++ and FORTRAN (there is no python version!)
  - OpenCL only for C
  - the C++ bindings will be dropped from the next MPI standard (only ISO C and FORTRAN 90 remain in MPI-3, C++ bindings are already deprecated in MPI-2.2)
- not all languages/libraries exist for all hardware platforms

SMP: ccNUMA

NUMA: Non Uniform Memory Access



It is important to keep data in caches coherent

$\longrightarrow$ ccNUMA architecture

ccNUMA requires special interconnect between nodes (low latency, high bandwidth)

does not scale as good as distributed memory parallelism (e.g. with MPI) due to necessary cache coherence

Work/Data Distribution

- Work decomposition
  (based on loop decomposition)

  do i=1,100 ->
  - do i=1,25
  - do i=26,50
  - do i=51,75
  - do i=76,100

- Data decomposition
  (all work for the local portion of data is done by local processor)

  A(1:40,1:100) ->
  - A(1:20,1:50)
  - A(1:20,51:100)
  - A(21:40,1:50)
  - A(21:40,51:100)

- Domain decomposition
  (decomposition of work and data is done in a higher model)

Parallel Programming Models

Hardware independent (more or less):

- OpenMP
  - Shared Memory Directives
  - to define the work decomposition
  - no data decomposition
  - synchronization is implicit (can be also user-defined)
- OpenCL (Open Compute Language)
- HPF (High Performance Fortran)
  - Data Parallelism
  - User specifies data decomposition with directives
  - Communication (and synchronization) is implicit
- MPI (Message Passing Interface), PVM
  - User specifies how work & data is distributed
  - User specifies how and when communication has to be done
  - by calling MPI communication library-routines

Hardware dependent:

- IBM Cell SDK
- nVidia CUDA
- SSE/MMX/. . . for x86 processors

Distribution Methods

decomposition	easiest programming interface
work	OpenMP
data	HPF
domain	MPI

Program Optimization

Different optimization goals and strategies:

- speed (Flops)
- memory usage
- portability
- maintainability
- programming effort/time

NB! Most of these goals are not compatible with each other!

OpenMP

- most OpenMP constructs are compiler directives of pragmas
- focus is to parallelize loops
- an incremental approach to parallelism is offered

Serial Program:

```
void main()
{
  double foo[1000];
  int i;

  for(i=0;i<1000;i++){
    do_huge_calc(foo[i]);
  }
}
```

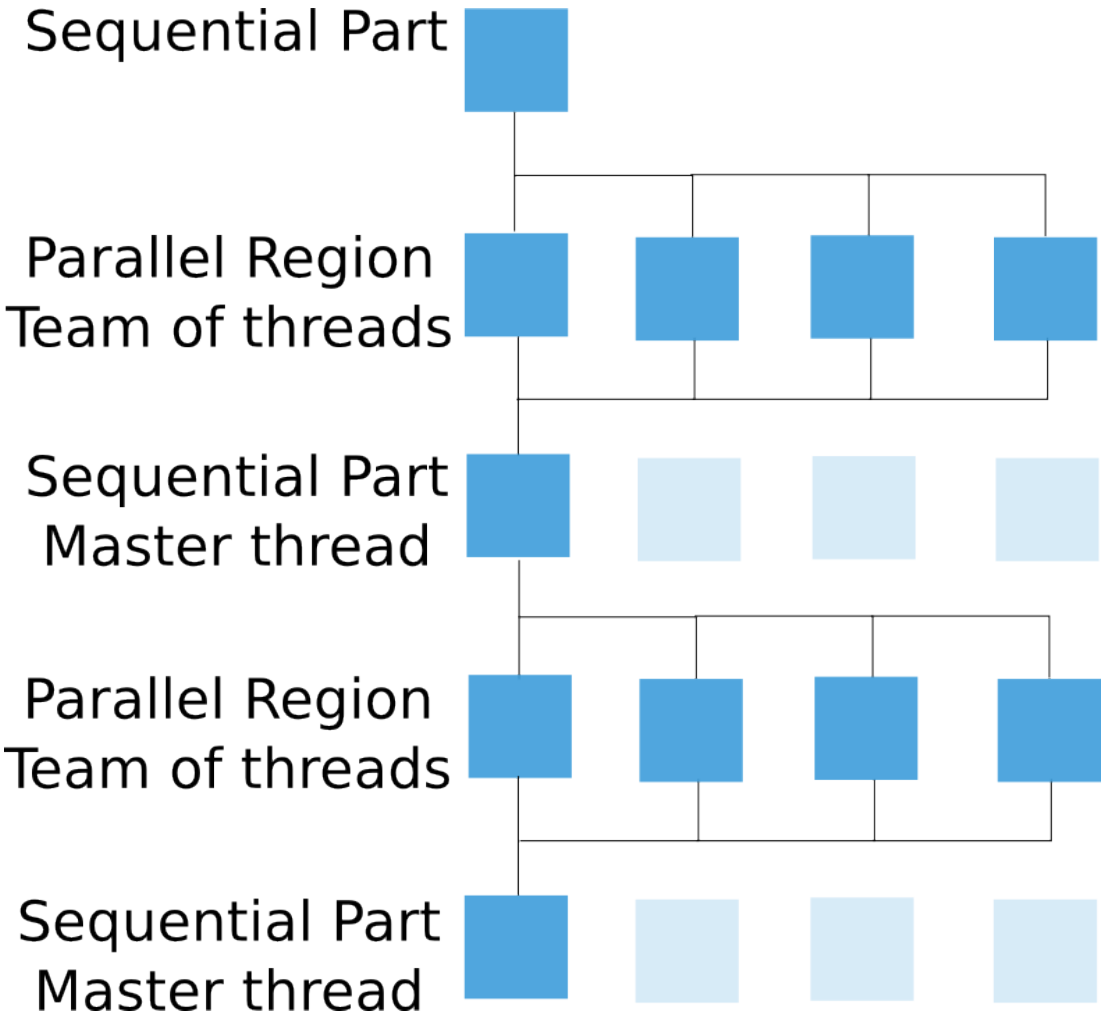
Parallel Program:

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

OpenMP Programming Model

- OpenMP is a shared memory model (SMP)
- workload is distributed between threads
- enabled via a compiler switch (`-fopenmp` for GCC)
- variables can be
  - shared among threads
  - duplicated for each thread
- unintended sharing of data leads to race conditions
  race condition: when the output of the program changes as the threads are scheduled differently
- control race conditions:
  use synchronization to prevent data conflicts

OpenMP Execution Model



OpenMP Parallel Region

Fortran:

```
!$OMP PARALLEL
  code
!$OMP END PARALLEL
```

C/C++:

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

OpenMP Directive Format: C/C++

- **`#pragma`** directives – case sensitive
- Format:
  `#pragma` `omp` directive_name [clause [[,]clause] . . .] newline
- Conditional compilation

```
#ifdef _OPENMP
   printf("number of processors: %d\n",get_num_procs());
#endif
```

- include library functions

```
#ifdef _OPENMP
#include <omp.h>
#endif
```

- constant `_OPENMP` is defined when `gcc -fopenmp` is used

OpenMP Data Scope Clauses

- `private` (list)
- `shared` (list)
- if not specified defaults to `shared`, but
  - stack (local) variables in called sub-programs are PRIVATE
  - automatic variables within a block are PRIVATE
  - loop control variables of parallel OMP DO/for are PRIVATE

Recommendation: Avoid private variables, use local variables instead (in C/C++).

OpenMP Environment Variables

- `OMP_NUM_THREADS`
  - sets number of threads
  - if dynamic adjustment is enabled: maximum number of threads
  - `setenv OMP_NUM_THREADS 4` [csh,tcsh]
  - `export OMP_NUM_THREADS=4` [sh, ksh, bash]
- `OMP_SCHEDULE`
- applies only to `DO/for` directives that have schedule type `RUNTIME`
- sets schedule type and chunk size
- `setenv OMP_SCHEDULE "GUIDED,4"` [csh,tcsh]
- `export OMP_SCHEDULE="GUIDED,4"` [sh, ksh, bash]

OpenMP Runtime Library

- C/C++:
  `#include <omp.h>`
  Fortran:
  `!$ INCLUDE 'omp_lib.h'` or `!$ USE omp_lib`
  (availability implementation dependent)
- `int omp_get_num_threads(void);`
  returns number of threads currently in the team of the parallel region
- `int omp_get_thread_num(void);`
  returns the number of the thread in the team. Master thread is 0.

OpenMP Work Sharing Constructs

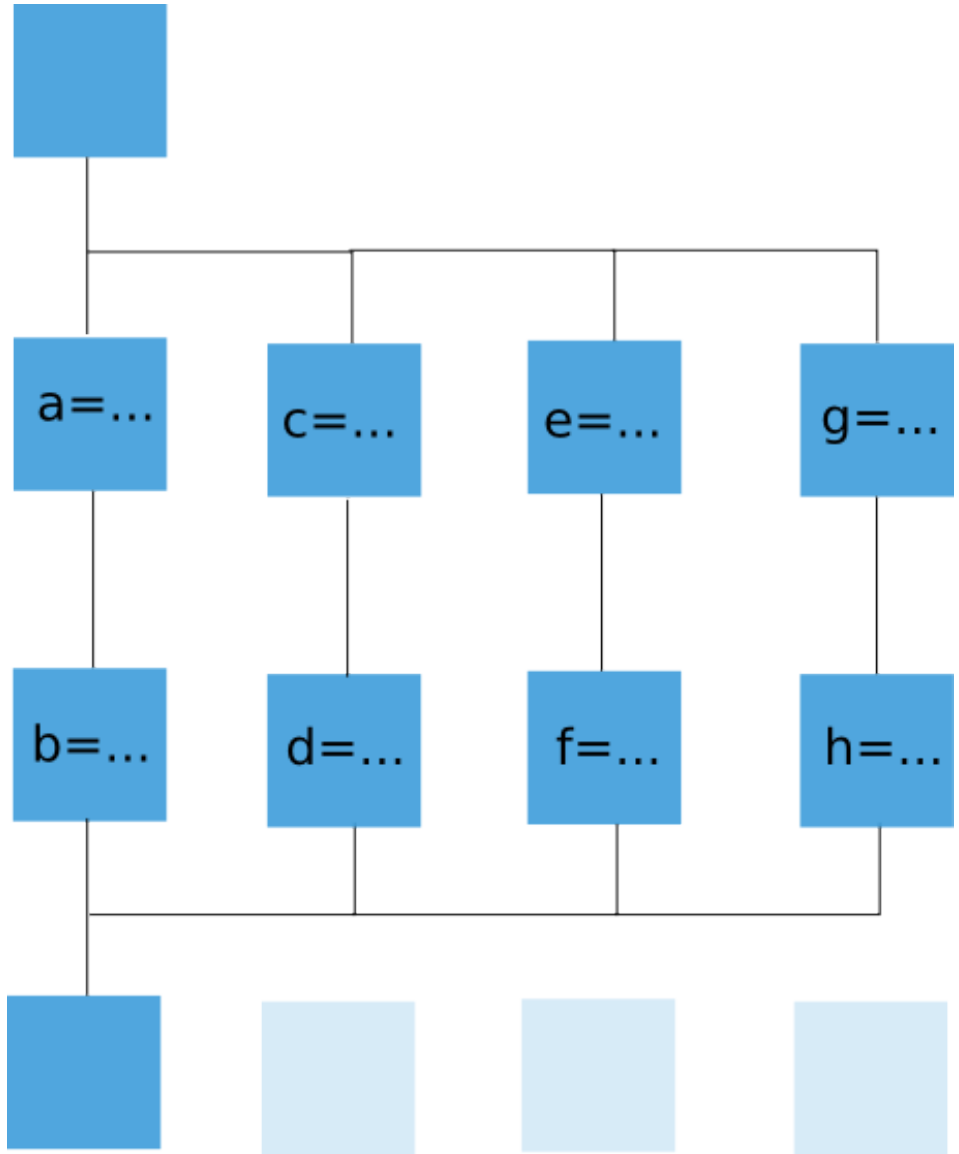
- `sections`
- `for` (C/C++)
- `do` (Fortran)
- `workshare` (Fortran)
- `single`

divide execution of enclosed code among the team
must be within parallel region
they do not launch new threads
no barrier on entry

OpenMP `sections` Directive

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=...;}
 } /* end omp sections */
} /* end omp parallel */
```



OpenMP `do/for` Directive

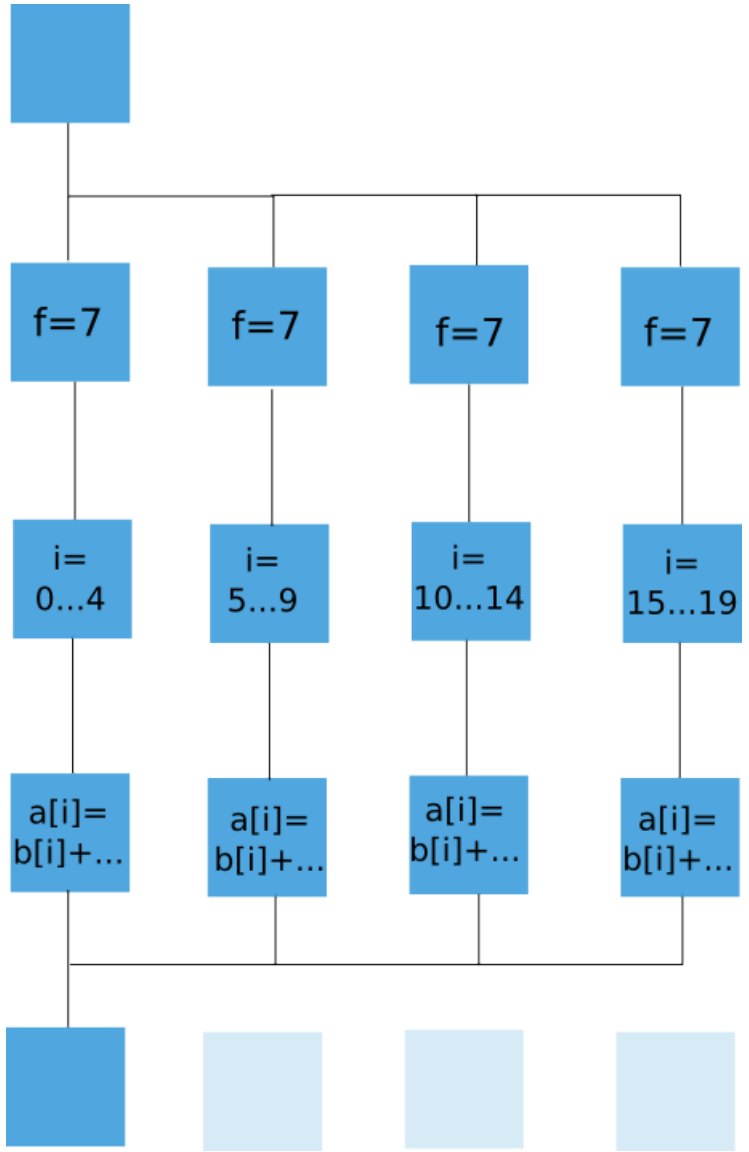
C/C++:

```
#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 `reduction` Clause

`reduction (operator:list)`
performs a reduction on the variables that appear in `list`, with the operator `operator`
operator: one of

- C/C++: +,*,-,&,^,|,&&,||
- Fortran: +,*,-, .and., .or., ,eqv., .neqv., max, min, iand, ior, ieor

variables must be `shared`
at the end of the `reduction` the shared variable is updated with the result.

OpenMP `reduction` Example

C/C++:

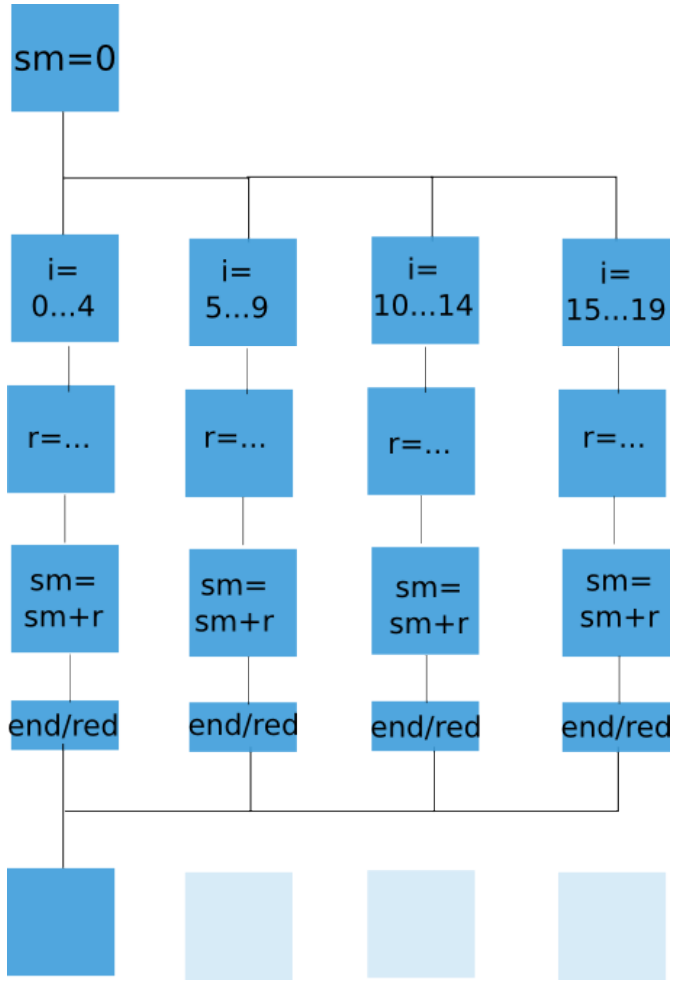
```
sm=0;
#pragma omp parallel for reduction(+:sm)
for(i=0;i<20;i++)
{
  double r;

  r= work(i);

  sm=sm+r;

} /* omp end parallel for */
```

[There is a combined `parallel do/for` directive for parallel regions that contain a single do/for.]



OpenMP Errors

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 access is undefined, i.e. unsynchronized
  - the outcome of a program depends on the detailed timing of the threads in the team
  - often caused by unintended share of data
- Deadlock
  - threads lock up waiting on a locked resource that will never become free

OpenMP Race Conditions – Example 1

```
#pragma omp parallel
{
#pragma omp sections
 a=b+c;
#pragma omp section
 b=a+c;
#pragma omp section
 c=b+a;
} /* omp end parallel sections */
```

OpenMP Race Conditions – Example 2

```
#pragma omp parallel shared(x), private(tmp)
{
 id=omp_get_thread_num();
#pragma omp for reduction(+:x) nowait
 for(i=1;i<100;i++)
   {
   tmp=work1(i);
   x=x+tmp;
   } /* omp end for reduction */
 y(id)=work2(x,id);
/* omp end parallel */
```

OpenMP Summary (1)

- standardized compiler directives for shared memory programming
- fork-join model based on threads
- support from (relevant) hardware vendors
- incremental approach for parallelism
- allows to keep single source for parallel and sequential execution
- race conditions and deadlock possible
- use tools to check for race conditions

NB! Single Source

Don't fork the code for parallelization, keep a single source tree!

Thread Checker

Goals:

- detect race conditions
- other parallelizations errors, like missing firstprivate

NB!

OpenMP parallelizations should never be used in production without verification with race-condition checking tools!

Parallel Debugging

- Intel Thread Checker (needs Intel C/FORTRAN Compiler)
  Linux and Windows; needs Intel compiler; commercial:
  - C++ Compiler prof. Linux 499,- + VAT (download), 539,- + VAT (CD)
  - Compiler suite prof. Linux (C++ and FORTRAN) 1099,- + VAT (CD)
  - Thread Checker Linux 409,- + VAT (download), 449,- + VAT (CD)
  - academic pricing on request
- Portland Group pgdbg and compiler
  commercial (akad.: C/C++/FORTRAN 699,-, C 299,-, FORTRAN 499,-)
- Sun/Oracle Solaris Studio Thread Analyzer
  Linux, Solaris; free (but closed source)
- maybe PathScale Eko with pathdb (or path64)
- Helgrind (Valgrind suite)
  Linux (Posix) only; free open-source
- DRD (Valgrind suite)
  Linux (Posix) only; free open-source
  (gcc needs to be compiled with `--disable-linux-futex`)
- ThreadSanitizer
  Linux (based on Valgrind), Windows (based on PIN); free open-source

Race Checker: Method

- Compile your OpenMP program with thread checker/debugging info
- start and execute with race checker
  - executed on 1 thread
  - verifying all memory accesses
  - $\sim$ 300 times slower than normal execution (use small but *relevant* data set)
- invoke analysis tool
  - error report
  - with references to your source code
- try to find the parallelization bugs in your code
- try to correct these (without modifying the serial semantics of the program
- compile and execute again
- repeat until all errors are resolved

Intel Thread Checker: Processing

TCI-mode (requires ICC):

compile	`icc -tcheck -openmp -g -o myprog myprog.c`
run	`tcheck_cl -w 90 -o myprog.txt ./myprog`
text output	`tcheck_cl -f txt -w 130 threadchecker.thr`
csv output	`tcheck_cl -f csv threadchecker.thr`

good tool

Sun/Oracle Thread Analyzer

Used with Sun/Oracle Solaris Studio

compile	`cc -xinstrument=datarace source.c`
run	`collect -r [ race | deadlock ] a.out`
display	`er_print [-race | -deadlock] tha.1.er`
display (GUI)	`tha tha.1.er`

untested

Valgrind-DRD

Requires gcc > 4.2 compiled with `--disable-linux-futex` (e.g. use `valgrind-3.6.0~svn11254/drd/scripts/download-and-build-gcc`) and recent Valgrind (SVN or debian/squeeze should be sufficient).

compile `gcc -g -fopenmp source.c`

set gcc `export CC=/path/to/gcc`

set libs `export LD_LIBRARY_PAT=/path/to/libs`

run
```
valgrind --tool=drd --check-stack-var=yes
    --read-var-info=yes --first-race-only=yes a.out
```

take care to use the futex-less gcc and libs! (most distributions have futex enabled)

Didn't find all the data-races in my tests.

Valgrind-Helgrind

Requires gcc > 4.2 compiled with `--disable-linux-futex` (e.g. use `valgrind-3.6.0~svn11254/drd/scripts/download-and-build-gcc`) and recent Valgrind (SVN or debian/squeeze should be sufficient).

compile `gcc -g -fopenmp source.c`

set gcc `export CC=/path/to/gcc`

set libs `export LD_LIBRARY_PAT=/path/to/libs`

run
```
valgrind --tool=helgrind
    --check-stack-var=yes a.out
```

take care to use the futex-less gcc and libs! (most distributions have futex enabled)

Didn't find all the data-races in my tests.

Thread Checker – Summary

- Intel Thread Checker finds the locations of race conditions, but the programmer must find the reason
- pgdbg, pathdb and Thread Analyser: untested
- Valgrind DRD/Helgrind didn't find all races
- Source code instrumentation returns an important error report (executed with 1 thread)
- programmer has to eliminate all errors or must be sure that the reported error is a "false positive" (note in source code with sign. of programmer)

It is absolutely necessary to use a tool to check for race-conditions!

And . . . I think I will stop here

Acknowledgements:

- Thanks to Eero Vainikko for inviting me!