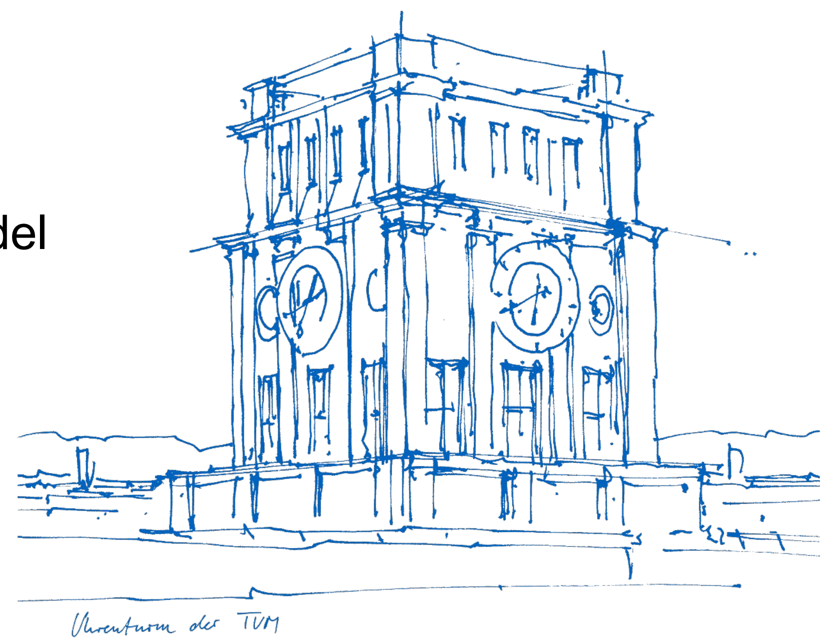
Lecture IN-2147
Parallel Programming

Martin Schulz
Technical University of Munich
Department of Computer Engineering

Lecture 3: OpenMP 101

- Seg. 11: OpenMP and its Execution Model
- Seg. 12: OpenMP Syntax and Basics
- Seg. 13: Data Sharing in OpenMP
- Seg. 14: Synchronization in OpenMP



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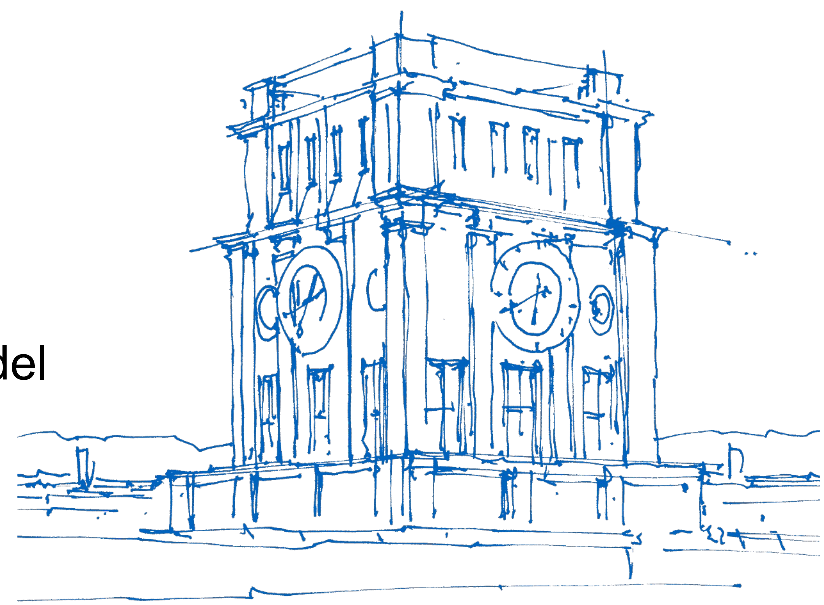
Lecture 3: OpenMP 101

- Performance Aspects for Threading
- Seg. 10: Other Thread APIs
- Seg. 11: OpenMP and its Execution Model
- Seg. 12: OpenMP Syntax and Basics
- Seg. 13: Data Sharing in OpenMP
- Seg. 14: Synchronization in OpenMP



Uhrenturm der TUM

Performance Aspects for Threading

Overheads

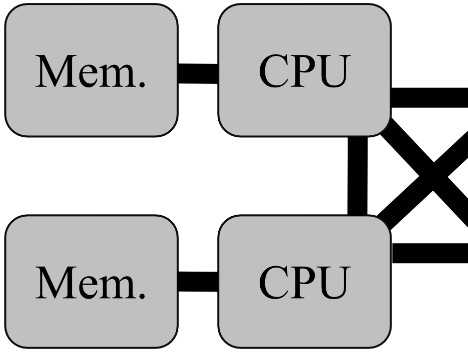
- Thread creation and destruction can be expensive operations
- Ensure large parallel regions or “park” threads

Lock contention

- Locks are low-overhead when few threads try access them
- Overhead grows with more threads accessing them more often

Thread pinning

- For system-level threads the OS does scheduling
  - Mapping of SW to HW thread
  - Determines the location of a thread’s execution
- Large impact on performance
  - Determines what is needed to share information
  - NUMA properties
- Pinning, fixing a SW thread to a (group of) HW thread(s)
  - Thread attributes, libraries like libNUMA (see `man numa`)



Good use of caches, avoidance of false sharing

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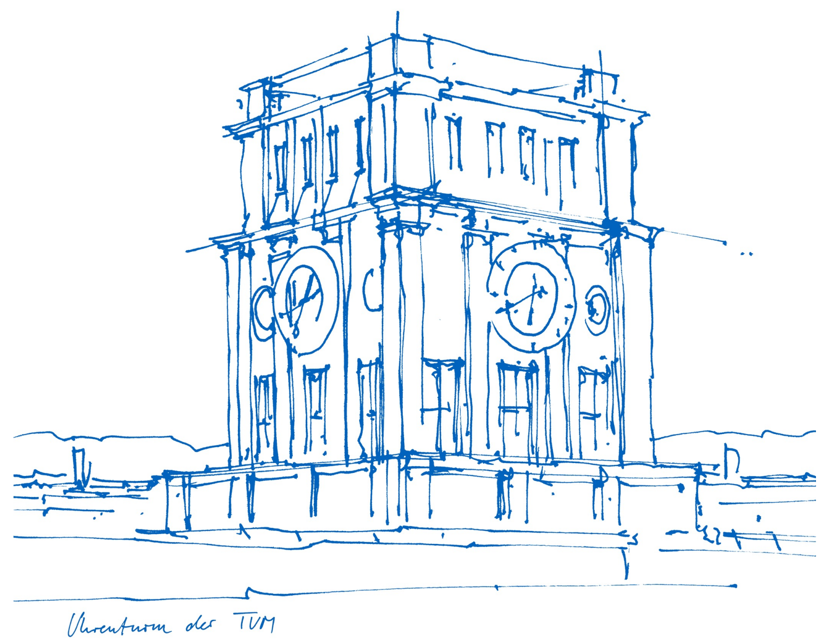
Segment 10
Modern Thread APIs



Different Thread APIs

Native thread APIs per system

- POSIX Threads
- Win32 Threads
- Solaris Threads

Native thread APIs per language

- C++ threads
- Java threads
- Rust threads

(requires a runtime system)

Portable standards

- OpenMP

Many custom/research packages

- Often mapped to native APIs
- Often user-level threads

Motivation for custom APIs

- Lower overhead
- Customized for particular tasks
- Custom hardware with special properties

Language APIs can Simplify Usage (e.g., C++)

```
#include <string>
#include <iostream>
#include <thread>
using namespace std;

// The function we want to execute on the new thread.
void task1(string msg)
{ cout << "task1 says: " << msg; }

int main()
{
   // Constructs the new thread and runs it. Does not block.
   thread t1(task1, "Hello");

   // Do other things...

   // Join threads, blocks until completion
   t1.join();
}
```

Task to be run in thread

Fork

Join

On G++, compile with -std=c++0x -pthread.

Source: https://stackoverflow.com/questions/266168/simple-example-of-threading-in-c

Mutex Example C++

```cpp
#include <iostream>
#include <thread
#include <mutex>

std::mutex mtx;

void print_thread_id (int id)
{
   mtx.lock();
   std::cout <<
      "thread #" << id << '\n’;
   mtx.unlock();
}
```

Declaration

Lock

Unlock

```cpp
int main ()
{
   std::thread threads[10];

   // spawn 10 threads
   for (int i=0; i<10; ++i)
      threads[i] =
         std::thread(
         print_thread_id,i+1);

   for (auto& th : threads)
      th.join();

   return 0;
}
```

Source: https://www.cplusplus.com/reference/mutex/mutex/lock/

Example: Java threads

```
public class ThreadExample
{
  public static void main(String[] args)
  {
    System.out.println(Thread.currentThread().getName());

    for(int i=0; i<10; i++)
    {
      new Thread("" + i)
      {
        public void run()
        {
          System.out.println("Thread: " + getName() + " running");
        }
      }.start();
} } }
```

New Thread Declaration

Task to be run
in thread (class)

Fork / Thread Start

Class also has a “join” method

Example: Java Locks

```
public class Counter
{
   private Lock lock = new Lock();
   private int count = 0;

   public int inc()
   {
      lock.lock();
      int newCount = ++count;
      lock.unlock();
      return newCount;
   }
}
```

Declaration

Lock

Unlock

Recap: Lecture 2 - Threading

A thread is a stream of execution

Hardware threads
- Implementation of the “von Neumann” control unit (CU)
- Complicated by multi-/many core and Hyperthreading/SMT

Software threads are abstracting execution streams for the programmer
- Distinguish user- and system-level threads
- Hybrid systems exist in some operating systems
- Real concurrency has to be layered on top of system-level threads

Thread execution by mapping SW thread to HW threads
- HW thread will execute SW thread
- Mapping (which core, socket, …) important for performance

Widely available and standardized API: POSIX threads
- Routines for thread creation/destruction
- Several synchronization constructs, incl. mutexes and condition variables

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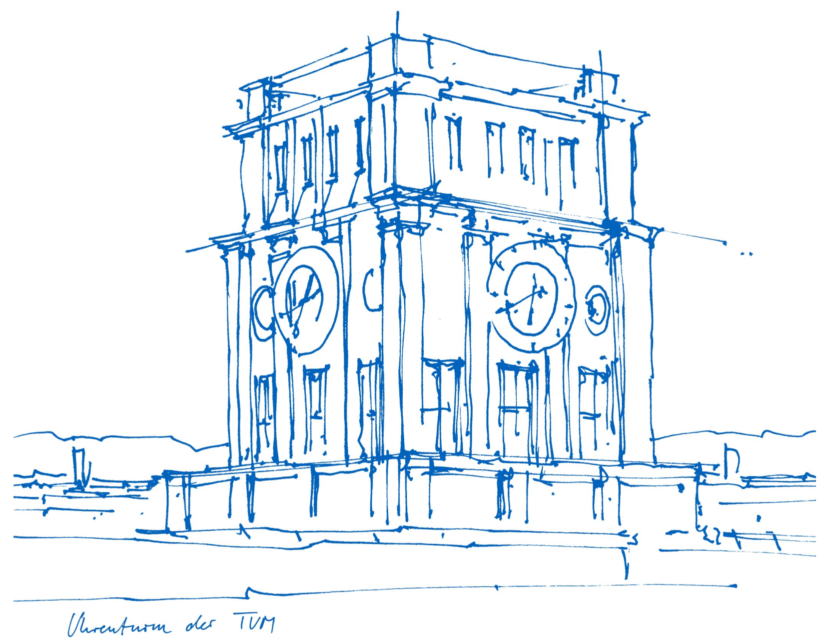


Segment 11
OpenMP and its Execution Model

Pros and Cons of Using Pthreads

Pthreads represent direct abstraction of system-level parallelism

- Direct map to underlying hardware threads (in most cases)
- Even parallel loops are difficult to think about

Association of data and threads is up to the programmer

- No program construct to do this
- Data locality has to be done explicitly

Need to manage data visibility by hand

- Which variables are per thread?
- Which variables are shared across all threads?

Simple synchronization primitives

- Locks and condition variables
- Not sufficient to do easy parallel coordination

Finding a Higher Level of Abstraction

Initially, each OS had its own threading abstraction
- All low-level and library based
- Even with the standard Pthreads,

In the 1990's several vendors supplied their own language extensions
- Driven by rising popularity of shared memory machines
- Mainly as extensions to Fortran
- Users could specify parallel loops
- A compiler would then translate the code to a threaded program

Very helpful for users
- Small, often incremental additions to code
  - In many cases, one line or one pragma
  - Codes stayed readable
- Compiler/runtime would do the engineering work

But: each vendor had their extensions, which made codes non-portable
- First attempt at standardizing failed (ANSI X3H5) in 1994
- A few years later, another attempt led to OpenMP

OpenMP = Open Multi-Processing

Standard for writing parallel programs, mainly “on-node”

- Standardization across many vendors, systems, architectures, …
- “Lean and Mean” – simple API to achieve complex goals
- Ease of Use
- Portability

Managed by the OpenMP ARB

- Architecture Review Board
- Independent non-profit organization
- Members are companies, universities, research labs

First version published in 1997

- Many advances since then
  - Tasking, SIMD, GPU support
- Currently at Version 5.2, published in November 2021
- All documents (and more) at www.openmp.org

OpenMP

OpenMP is …

... an Application Program Interface (API) that may be used to program multi-threaded, shared memory parallelism (plus accelerators)

... comprised of three primary API components:

- Compiler Directives (for C/C++ and Fortran)
- Runtime Library Routines
- Environment Variables

OpenMP is not ...

... intended for distributed memory systems

... necessarily implemented identically by all vendors

... guaranteed to automatically make the most efficient use of shared memory

... required to check for data dependencies, race conditions, deadlocks, etc.

... designed to handle parallel I/O

A Simple Example

```
#include <omp.h>

main(){
    #pragma omp parallel
    {
     printf("Hello world");
    }
}
```

```
> export OMP_NUM_THREADS=2
> a.out
Hello world
Hello world
```

```
> export OMP_NUM_THREADS=3
> a.out
Hello world
Hello world
Hello world
```

Compilation

- `icc -O3 -openmp openmp.c`
- `gcc -O3 -fopenmp openmp.c`

- This differs between compilers

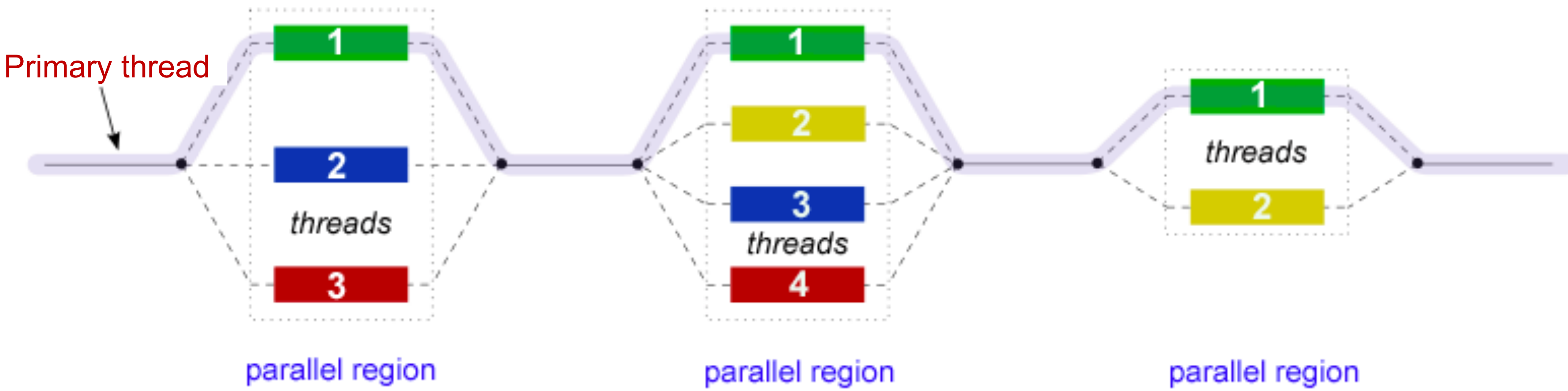
Fork/Join Execution Model

Older OpenMP Versions refer to a “master” thread (new deprecated)

Parallel Regions

1. An OpenMP-program starts as a single thread (*primary thread*).
2. Additional threads are created when the master hits a parallel region.
3. After the parallel region, the new threads are given back to the runtime
4. The primary thread continues after the parallel region.

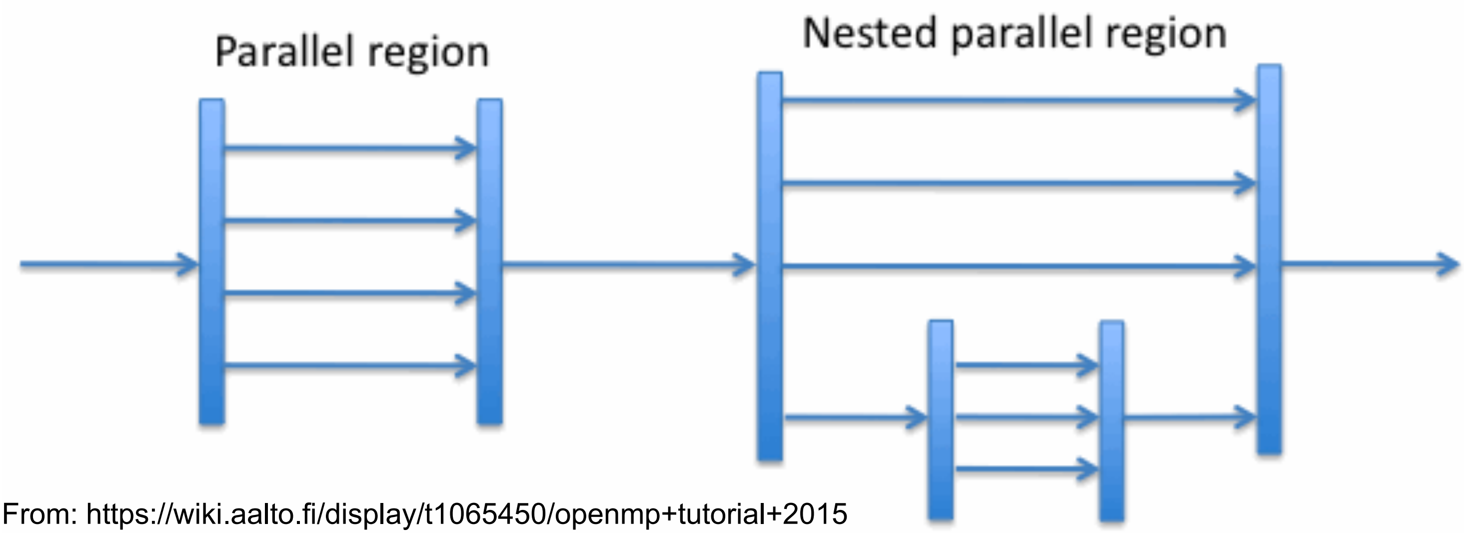
All threads in the team are synchronized at the end of a parallel region via a barrier.



Source: LLNL tutorial by Blaise Barney, adapted to OpenMP 5.2

Nested Parallelism

OpenMP threads can themselves create parallel regions



From: https://wiki.aalto.fi/display/t1065450/openmp+tutorial+2015

Noteworthy

- OpenMP is not required to spawn/use more threads in the nested region
  - It is compliant to just continue executing sequentially
- Mapping to hardware threads is up to the runtime

OpenMP Implementations

OpenMP is a language extension

- On top of C/C++ or Fortran
- Pragmas to the base language, which can be ignored

Consequence: need a new compiler

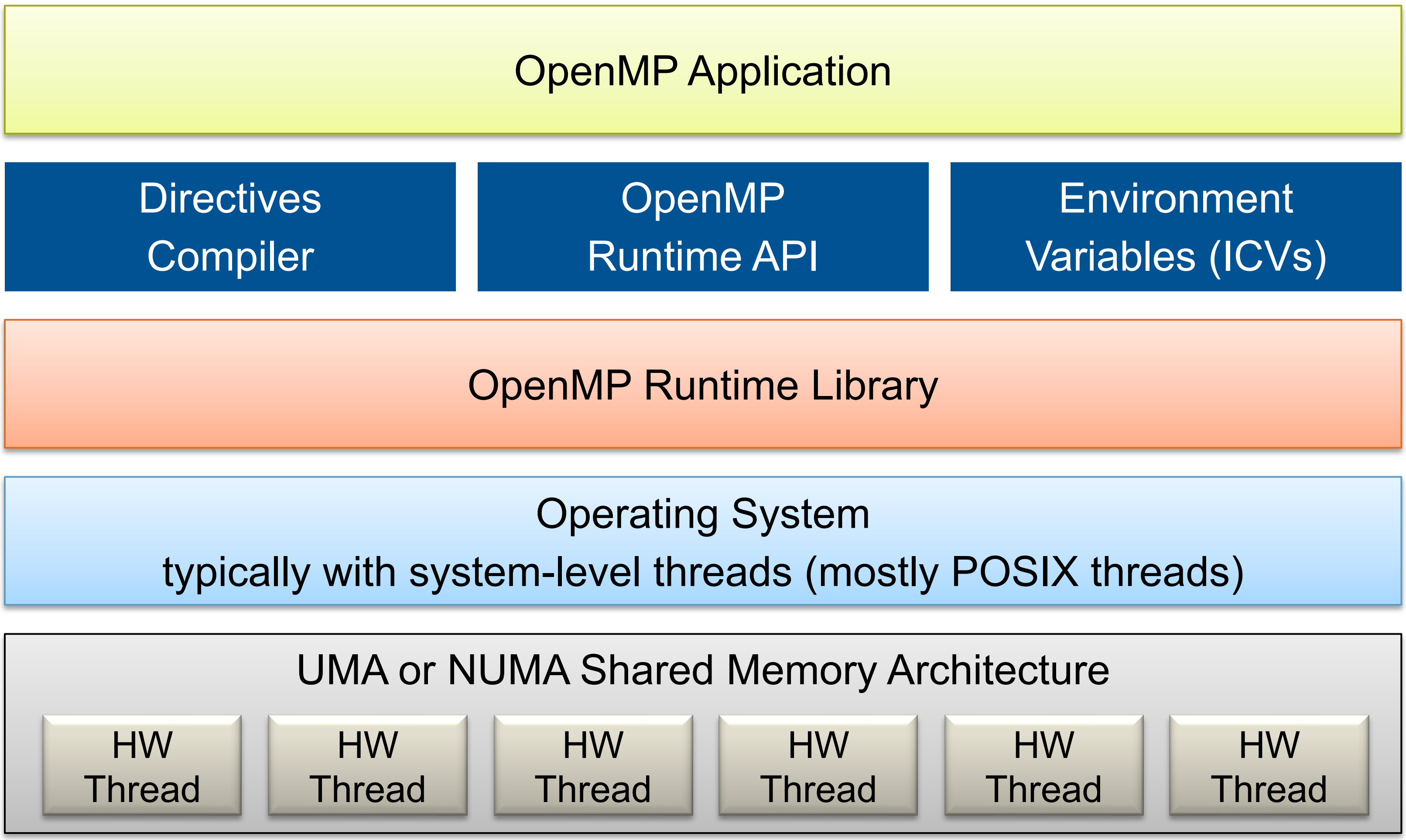
- Implemented within existing compilers
- Most compilers support this now: gcc, icc, LLVM, PGI, ...

Additionally: need a runtime system

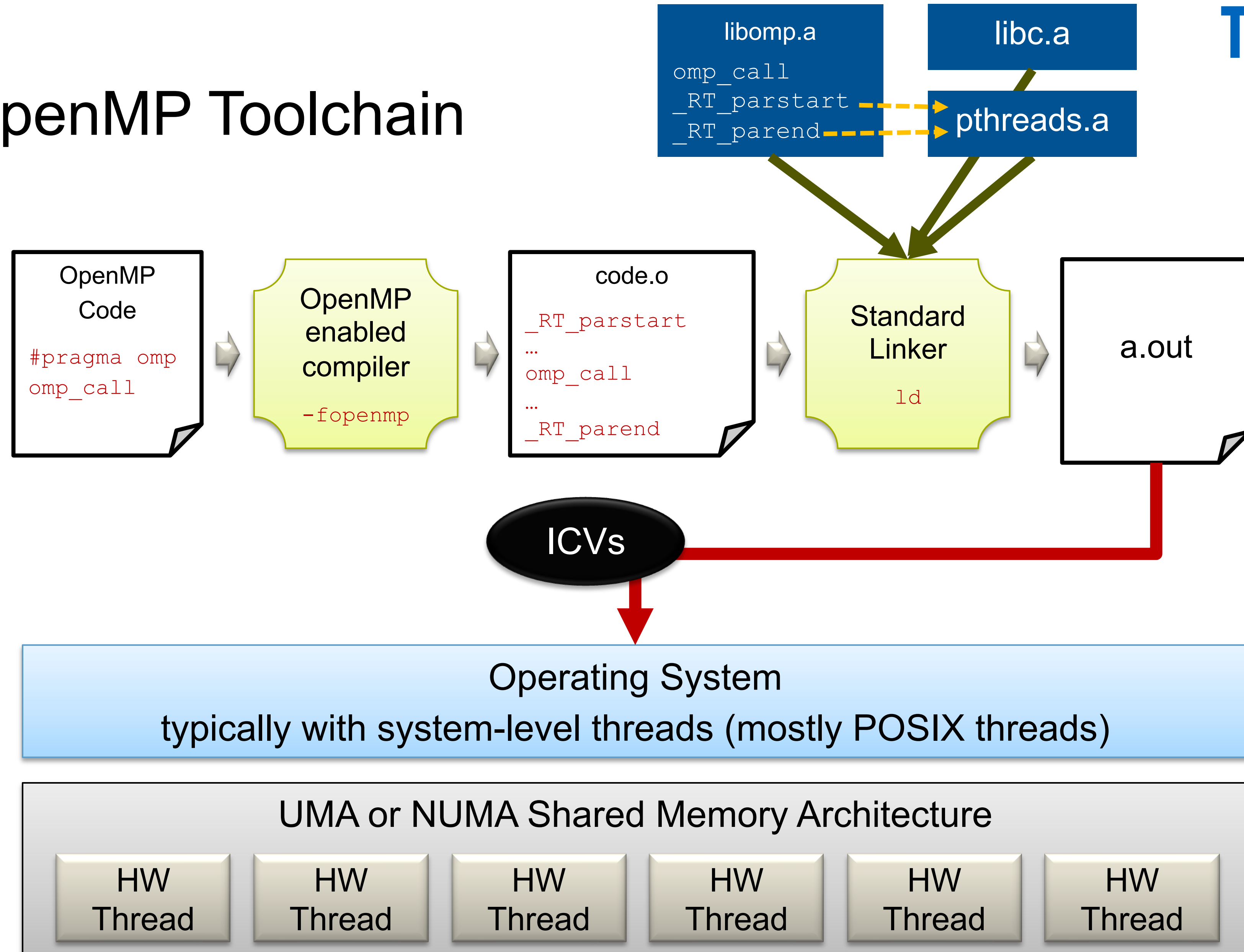
- Maps program to underlying thread package
- Often built on top of Pthreads
- Standard defines some user functions, but NOT the entire interface
- Two widely known open source systems: gomp and Intel‘s OpenMP/LLVM runtime

Well defined environment variables, also called „internal control variables“ or „ICVs“

OpenMP System Stack



OpenMP Toolchain



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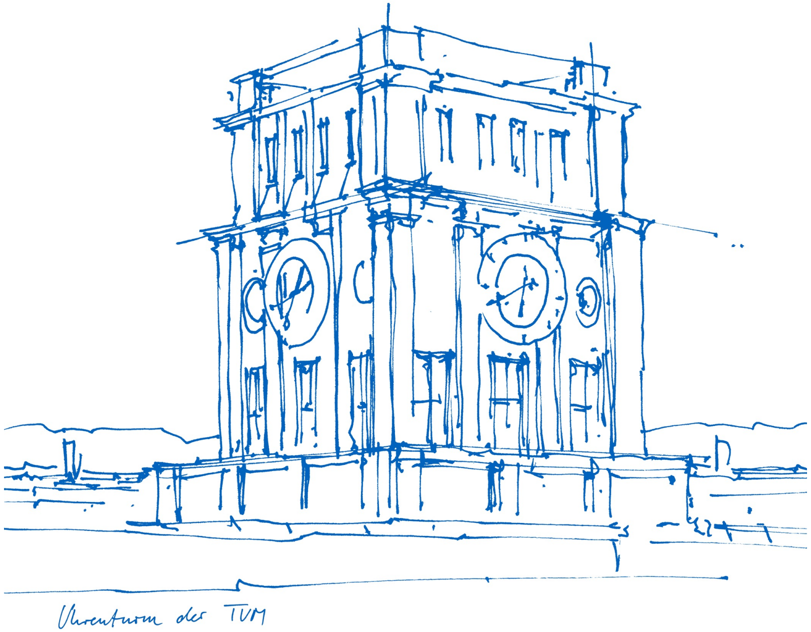
Segment 12 OpenMP Syntax and Basics



OpenMP Syntax

Most of the constructs in OpenMP are compiler directives

```
#pragma omp construct [clause [clause]…]
```

Example: `#pragma omp parallel`

Most OpenMP constructs apply to a “structured block”.

- A block of one or more statements
- With one point of entry at the top and one point of exit at the bottom
- Think: C/C++

```
{ … }
```

Additionally: runtime API

- Function prototypes and types in the `omp.h` header file
- Namespace: `omp_`

Fortran

OpenMP also defines pragmas for Fortran

- Same concepts and similar pragmas
- Different syntax
- Need to deal with scoping differently

```
!$OMP directive name  [parameters]
```

Example:

```
!$OMP PARALLEL DEFAULT(SHARED)
       write(*,*) ´Hello world´
!$OMP END PARALLEL
```

More on Directives Syntax

Directives can have continuation lines

- C
  **#pragma omp parallel private(i) **
  private(j)

- Fortran
  !$OMP *directive name first_part &*
  !$OMP continuation_part

Parallel Regions

Parallel regions are marked explicitly

```
#pragma omp parallel [parameters]
{
        block
}
```

Block executed in parallel by a *team of threads*

Degree of parallelism controlled by ICV

```
        OMP_NUM_THREADS
```

A Simple Example (repeated)

```
#include <omp.h>

main(){
    #pragma omp parallel
    {
     printf("Hello world");
    }
}
```

```
> export OMP_NUM_THREADS=2
> a.out
Hello world
Hello world

> export OMP_NUM_THREADS=3
> a.out
Hello world
Hello world
Hello world
```

Compilation

- `icc -O3 -openmp openmp.c`
- `gcc -O3 -fopenmp openmp.c`

- This differs between compilers

Sections in a Parallel Region

Parallel regions can have separate sections

```
#pragma omp sections [parameters]
{
 #pragma omp section
       { … block … }
 #pragma omp section
       { … block … }
  ...
}
```

Most “thread like” option

- Must be within a parallel region
- Each section within a sections block is executed once by one thread
- Threads that finished their section wait at an implicit barrier at the end of the sections region/block

Example: Sections

```
main(){
int a[1000], b[1000];

#pragma omp parallel
 {
 #pragma omp sections
  {
  #pragma omp section
  for (int i=0; i<1000; i++)
    a[i] = 100;
  #pragma omp section
  for (int i=0; i<1000; i++)
    b[i] = 200;
  }
 }
}
```

Example: Sections (shortcut)

```
main(){
int a[1000], b[1000];

#pragma omp parallel sections
 {


   #pragma omp section
   for (int i=0; i<1000; i++)
     a[i] = 100;
   #pragma omp section
   for (int i=0; i<1000; i++)
     b[i] = 200;

 }
}
```

Work Sharing in a Parallel Region

Need easy way to split tasks among threads
Most important construct: loops

```
main (){
int a[100];
#pragma omp parallel
 {
   #pragma omp for
    for (int i= 1; i<n;i++)
       a[i] = i;
 }
}
```

```
main (){
int a[100];


#pragma omp parallel for
    for (int i= 1; i<n;i++)
       a[i] = i;

}
```

Creates a parallel region
Splits iterations of `for` loop among threads

Parallel Loop

```
#pragma omp for [parameters]
    for ...
```

- The iterations of the do-loop are distributed to the threads
- There is no synchronization at the beginning
- All threads of the team synchronize at an implicit barrier
  - Unless the parameter **`nowait`** is specified
- Note: the expressions in the for-statement are very restricted

Iterations must be independent

- No data dependencies
- Can be executed in any order
- Programmer responsibility

How do Loops get Split up?

Iterations must be distributed to threads

Loop Schedule

- Defines how iterations are split up
  - Leads to the creation of “Chunks”
- Defines how chunks are mapped to threads

OpenMP offers several options

- Specified using the `schedule` parameter

Example:

```
#pragma omp for schedule(static)
```

Available Loop Schedules

`static`

- Fix sized chunks (default size is about n/t)
- Distributed in a round-robin fashion

`dynamic`

- Fix sized chunks (default size is 1)
- Distributed one by one at runtime as chunks finish

`guided`

- Start with large chunks, then exponentially decreasing size
- Distributed one by one at runtime as chunks finish

`runtime`

- Controlled at runtime using control variable

`auto`

- Compiler/Runtime can choose

Examples: Scheduling

```c
#define S 25
int main(int argc, char** argv)
{ int a[S],b[S],c[S];

#pragma omp parallel
{
 #pragma omp for schedule(static)
  for (int i=0; i<S;i++)
    a[i] = omp_get_thread_num();

 #pragma omp for schedule(dynamic, 4)
  for (int i=0; i<S;i++)
    b[i] = omp_get_thread_num();

 #pragma omp for schedule(guided)
  for (int i=0; i<S;i++)
    c[i] = omp_get_thread_num();
 }

 for (int i=0; i<S;i++)
    printf("Iter %4d: %4d %4d %4d\n",i,a[i],b[i],c[i]);
}
```

```
Iter    0:  0   3   2
Iter    1:  0   3   2
Iter    2:  0   3   2
Iter    3:  0   3   1
Iter    4:  0   1   1
Iter    5:  0   1   0
Iter    6:  0   1   0
Iter    7:  1   1   1
Iter    8:  1   0   1
Iter    9:  1   0   0
Iter   10:  1   0   0
Iter   11:  1   0   2
Iter   12:  1   1   1
Iter   13:  2   1   0
Iter   14:  2   1   2
Iter   15:  2   1   0
Iter   16:  2   3   2
Iter   17:  2   3   1
Iter   18:  2   3   0
Iter   19:  3   3   2
Iter   20:  3   0   0
Iter   21:  3   0   2
Iter   22:  3   0   1
Iter   23:  3   0   0
Iter   24:  3   1   2
```

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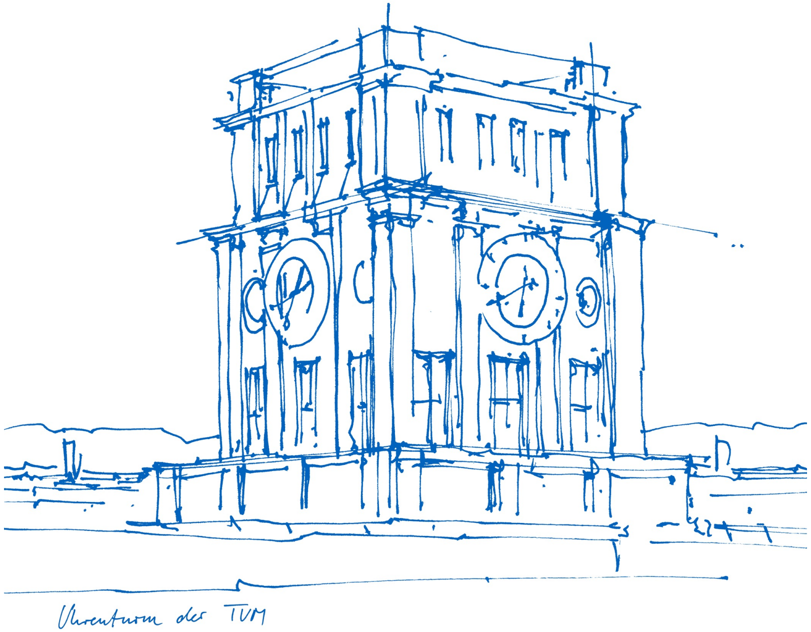
Segment 13
Data Sharing in OpenMP



Shared vs. Private Data

Important decision: visibility of data / variables

Shared data
- Accessible by all threads
- One copy for all threads
- Example: a reference a[5] to a shared array accesses

Private data
- Accessible only by a single thread
- Each thread has its own copy
- Example: iterator variables

The default for global variables: shared
Variables declared within the “dynamic extent” of parallel regions: local
- Includes routines called from parallel regions

Private clause for parallel loop

```
main (){
int a[100], t;

#pragma omp parallel
 {
   #pragma omp for private(t)
    for (int i= 1; i<n;i++){
       t=f(i);
       a[i]=t;
     }
 }
}
```

Global variable: a, t

Local variable: i

Variable t by default shared, but now “privatized”

Example / Thread Identities

```
main (){
int iam, nthreads;

#pragma omp parallel private(iam,nthreads)
 {
  iam = omp_get_thread_num();
  nthreads = omp_get_num_threads();
  printf("ThradID %d, out of %d threads\n", iam, nthreads);

  if (iam == 0)
    printf("Here is the Master Thread.\n");
  else
    printf("Here is another thread.\n");
 }
}
```

Example / Thread Identities – Better Option

```
main (){


#pragma omp parallel
 {
  int iam = omp_get_thread_num();
  int nthreads = omp_get_num_threads();
  printf("ThreadID %d, out of %d threads\n", iam, nthreads);

  if (iam == 0)
    printf("Here is the Master Thread.\n");
  else
    printf("Here is another thread.\n");
 }
}
```

Private Data Options

```
int i=3;
#pragma omp parallel for
  for (int j=0; j<4; j++)
    { i=i+1;
      printf("-> i=%d\n", i); }
printf("Final Value of I=%d\n", i);
```

Before	Loop	After
i = 3		i = 7
	i = 5	
	i = 4	
	i = 7	
	i = 6	

Before	Loop	After
i = 3		i = 4
	i = 4	
	i = 5	
	i = 5	
	i = 6	

```
int i=3;
#pragma omp parallel for private(i)
  for (int j=0; j<4; j++)
    { i=i+1;
      printf("-> i=%d\n", i); }
printf("Final Value of I=%d\n", i);
```

Before	Loop	After
i = 3	i = 3	i = 3
	i = ?	
	i = ?	
	i = ?	
	i = ?	

First/Last Private Data Options

```
int i=3;
#pragma omp parallel for firstprivate(i)
  for (int j=0; j<4; j++)
    { i=i+1;
      printf("-> i=%d\n", i); }
printf("Final Value of I=%d\n", i);
```

Before	Loop	After
i = 3	i = 3	i = 3
	i = 4	
	i = 4	
	i = 4	
	i = 4	

```
int i=3;
#pragma omp parallel for lastprivate(i)
  for (int j=0; j<4; j++)
    { i=i+1;
      printf("-> i=%d\n", i); }
printf("Final Value of I=%d\n", i);
```

Before	Loop	After
i = 3	i = 3	i = ?
	i = ?	
	i = ?	
	i = ?	
	i = ?	

```
int i=3;
#pragma omp parallel for firstprivate(i) \
                         lastprivate(i)
  for (int j=0; j<4; j++)
    { i=i+1;
      printf("-> i=%d\n", i); }
printf("Final Value of I=%d\n", i);
```

Before	Loop	After
i = 3	i = 3	i = 4
	i = 4	
	i = 4	
	i = 4	
	i = 4	

Summary: Sharing Attributes of Variables

`private(var-list)`
- Variables in var-list are private

`shared(var-list)`
- Variables in var-list are shared

`default(private | shared | none)`
- Sets the default for all variables in this region

`firstprivate(var-list)`
- Variables are private
- Initialized with the value of the shared copy before the region.

`lastprivate(var-list)`
- Variables are private
- Value of the thread executing the last iteration of a parallel loop in sequential order is copied to the variable outside of the region.

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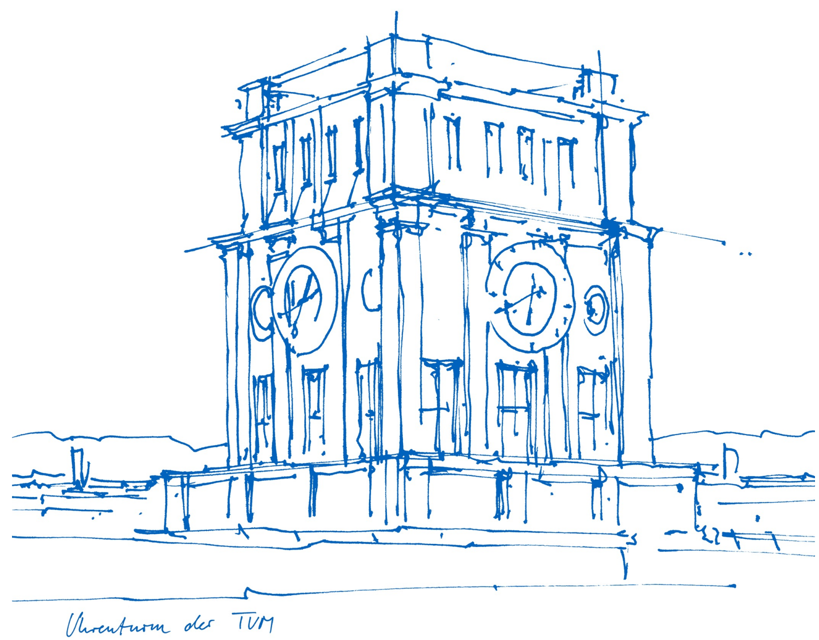
Segment 14
Synchronization



Data Synchronization

As with Pthreads, we need options to synchronize data accesses

- Communication is through shared variables
- Synchronization has to be separate

OpenMP offers a wide range of pragma based options

- Barriers
- Masked regions
- Single regions
- Critical sections
- Atomic statements
- Ordering construct

Additional runtime routines for locking

Barrier

Key synchronization construct

- Synchronizes all the threads in a team
- Each thread waits until all other threads in the team have reached the barrier

Each parallel region has an implicit barrier at the end

- Synchronizes the end of the region
- Can be switched off by adding `nowait`

Additional barriers can be added when needed

```
#pragma omp barrier
```

Warning

- Can cause load imbalance
- Use only when really needed

Master Region

```
#pragma omp master
        block
```

A master region enforces that only the master executes the code block
- Other threads skip the region
- No synchronization at the beginning of region

Possible uses
- Printing to screen
- Keyboard entries
- File I/O

Warning:
Deprecated

Masked Region

```
#pragma omp masked
        block
```

The **masked** construct (without arguments) declares a region that only the **primary** thread executes the code block

- Other threads skip the region
- No synchronization at the beginning of region

Possible uses

- Printing to screen
- Keyboard entries
- File I/O

Masked Region

```
#pragma omp masked [filter(integer-expression)]
         block
```

The **masked** construct (with arguments) declares a region that only the threads execute that are specified in the integer expression (relative to the current team)

- Other threads skip the region
- No synchronization at the beginning of region

Possible Uses

- Designate a different thread than the primary one for I/O
- Possibly combined with a “nowait” → can create overlap

Single Region

```
#pragma omp single [parameter]
        block
```

A single region enforces that only a (arbitrary) single thread executes the code block
- Other threads skip the region
- Implicit barrier synchronization at the end of region (unless **`nowait`** is specified)

Possible uses
- Initialization of data structures

Critical Section

```
#pragma omp critical [(Name)]
        block
```

Mutual exclusion

- A critical section is a block of code
- Can only be executed by only one thread at a time.
- Compare to Pthreads locks

Critical section name identifies the specific critical section

- A thread waits at the beginning of a critical section until its available
- All unnamed critical directives map to the same name

Keep in mind

- Critical section names are global entities of the program
- If a name conflicts with any other entity, program behavior is unspecified
- Avoid long critical sections for performance reasons

Atomic Statements

```
#pragma ATOMIC
     expression-stmt
```

The ATOMIC directive ensures that a specific memory location is updated atomically

Has to have the following form:
  - x binop= expr
  - x++ or ++x
  - x-- or --x
- where x is an lvalue expression with scalar type
- and expr does not reference the object designated by x

Equivalent to using critical section to protect the update

Useful for simple/fast updates to shared data structures
- Avoids locking
- Often implemented directly by native instructions

Simple Runtime Locks

In addition to pragma based options, OpenMP also offers runtime locks

- Same concept as Pthread mutex
- Locks can be held by only one thread at a time.
- A lock is represented by a lock variable of type omp_lock_t.

Operations

omp_init_lock(&lockvar)	initialize a lock
omp_destroy_lock(&lockvar)	destroy a lock
omp_set_lock(&lockvar)	set lock
omp_unset_lock(&lockvar)	free lock
logicalvar = omp_test_lock(&lockvar)	check lock and possibly set lock

returns true if lock was set by the executing thread.

Example: Simple Lock

```
#include <omp.h>
int id;
omp_lock_t lock;

omp_init_lock(lock);
#pragma omp parallel shared(lock) private(id)
{
  id = omp_get_thread_num();
  omp_set_lock(&lock); //Only a single thread writes
    printf("My Thread num is: %d", id);
  omp_unset_lock(&lock);

  while (!omp_test_lock(&lock))
    other_work(id);          //Lock not obtained
  real_work(id);             //Lock obtained
  omp_unset_lock(&lock);     //Lock freed
}
omp_destroy_lock(&lock);
```

locked

locked

Nestable Locks

Similar to simple locks

But, nestable locks can be set multiple times by a single thread.

- Each set operation increments a lock counter
- Each unset operation decrements the lock counter

If the lock counter is 0 after an unset operation, lock can be set by another thread

Separate routines for nestable locks

Look them up ☺

Ordered Construct

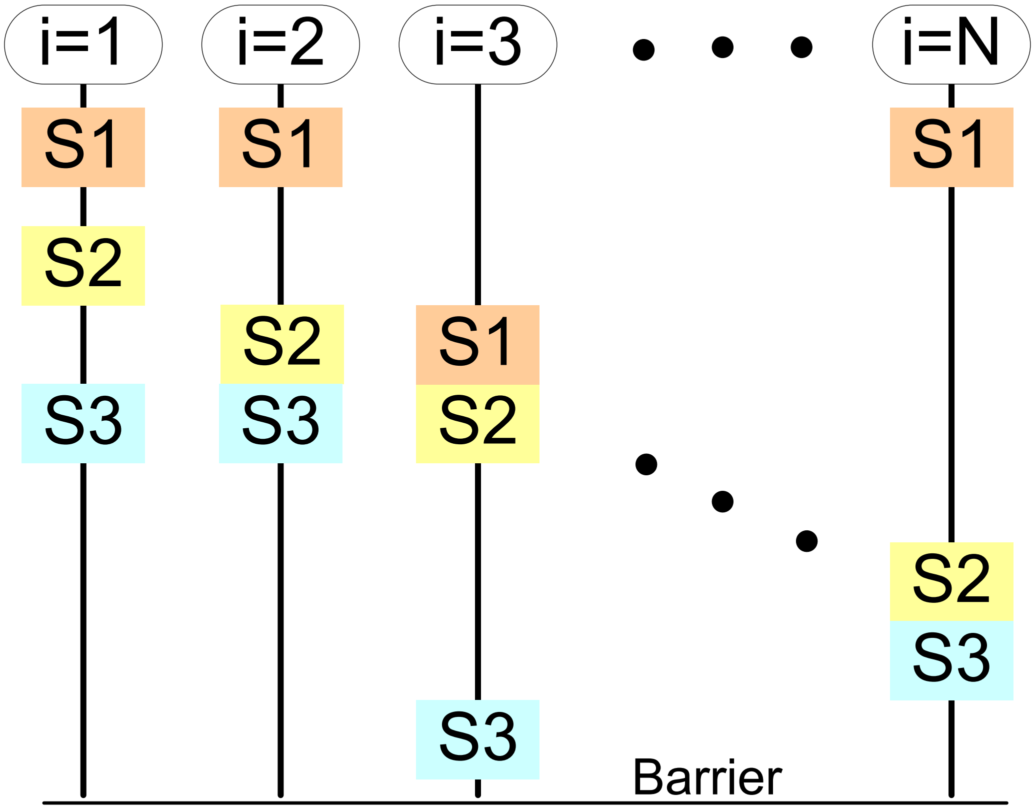
```
#pragma omp for ordered
    for (...)
     { ...
       #pragma omp ordered
       { ... }
       ...
     }
```

Construct must be within the dynamic extent of an `omp for` construct with an ordered clause.

Ordered constructs are executed strictly in the order in which they would be executed in a sequential execution of the loop.

Example: ordered clause

```
#pragma omp for ordered
for (...)
 { S1
  #pragma omp ordered
  { S2 }
  S3
 }
```



Summary: OpenMP 101

OpenMP was created to standardize the programming of shared memory systems

- First standard in 1997, currently at OpenMP 5.0
- Goals were easy of use, simplicity and portability

Key concepts

- Parallel regions
- Worksharing through parallel for loops
- Additional clauses to control distribution, synchronization, …
- Options to control data visibility/sharing

Programmer responsibility

- Ensure no loop dependencies exist
- Ensure the right variables or private or shared
- Ensure the necessary synchronization is added