703650 VO Parallel Systems WS2020/2021
OpenMP Basics

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Overview

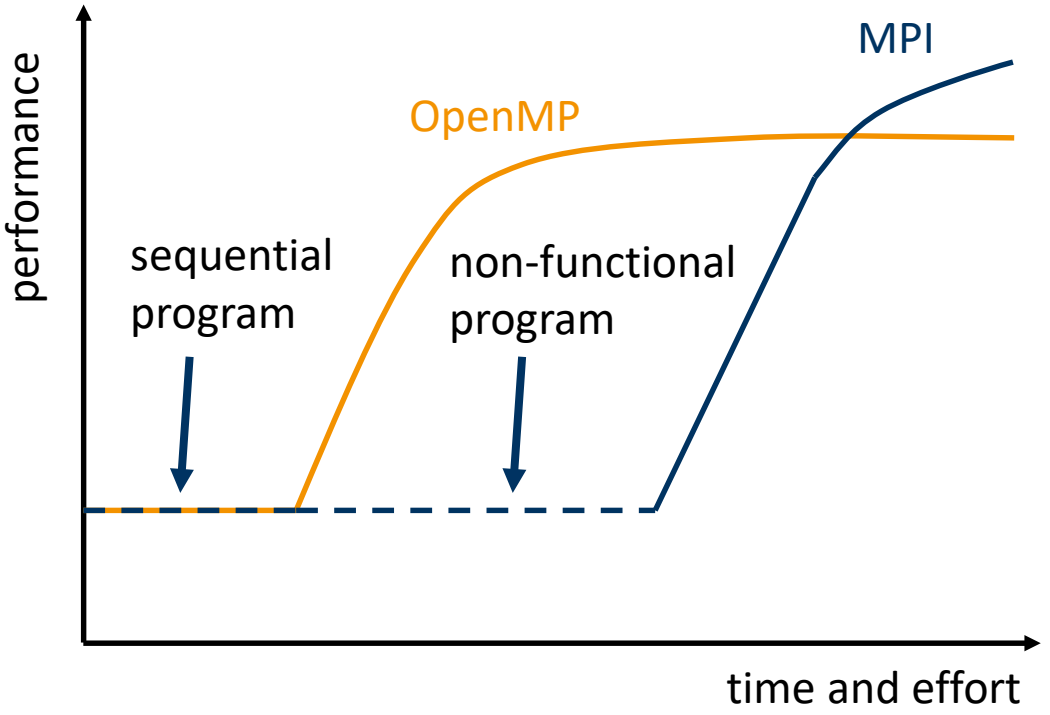
- main characteristics
- programming, execution and memory models
- directives
- Tales From the Proseminar

Motivation for Using OpenMP

- OpenMP is one of the easiest parallel programming models & widely available
  - however, restricted to shared memory and multi-threaded hardware
- modern hardware encourages use of such models
  - Marvell ARM: ThunderX3: 96 cores and 384 threads
  - AMD x86 desktop: Threadripper 3990X with 64 cores and 128 threads
  - AMD x86 server: 2x EPYC 77xx with 64 cores / 128 threads = 128/256
  - Intel x86 server: 8x Xeon Platinum 827x or 828x with 28 cores / 56 threads = 224/448
  - exotic hardware: SGI Altix UV (“Mach 2” @ JKU in Linz) with 4096/8192
- also enables access to up to e.g. 64 TB of RAM on SGI Altix UV systems

The Advantage of Incremental Parallelization

- MPI
  - initially a sequential program
  - start to parallelize
  - program won't work until major parts of parallelization present
- OpenMP
  - initially a sequential program
  - parallelize incrementally
  - program remains functional throughput parallelization process



OpenMP

- thread-based programming model for shared memory parallelism
- de-facto standard for C/C++ and Fortran
- maintained by the OpenMP Architecture Review Board
  - initial release in 1997 (version 1.0 for Fortran)
  - updates in 1998 (1.0 for C/C++), 2000 (2.0), 2005 (2.5), 2008 (3.0), 2011 (3.1), 2013 (4.0), 2018 (5.0)
  - this slide set assumes at least OpenMP 3.1!

OpenMP Implementations

- many implementations available
  - GCC, LLVM, Intel, Microsoft, etc.
  - allow to run OpenMP basically on every platform (portability)
    - that provides decent performance…
  - compiler and runtime support required
    - sometimes interchangeable components
    - check https://www.openmp.org/resources/openmp-compilers-tools/ for compiler support
- do not confuse implementation adherence with specification adherence
  - many minor semantics in OpenMP are implementation-defined

Main Characteristics

- compiler-based parallelization model
  - tell compiler what code to parallelize and where to put synchronization points
  - tell compiler whether to share data among threads or create private copies
  - but compiler cannot/will not check semantic correctness
    - Won’t somebody please think of the compiler developers?

- allows incremental parallelization

- C/C++ and Fortran bindings
  - even a research compiler for Java is available…

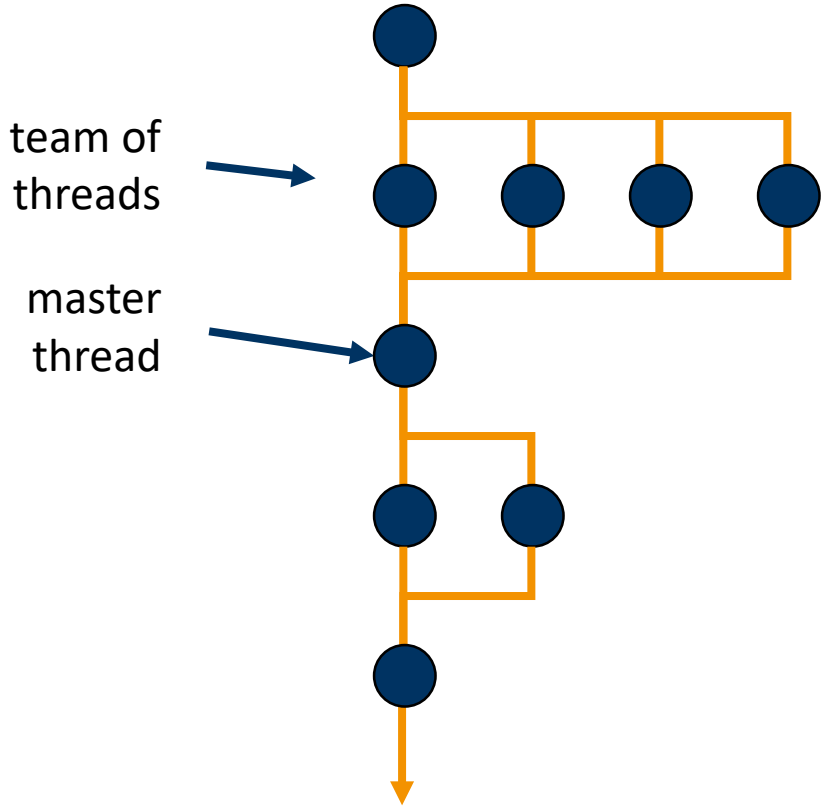
How to Choose between OpenMP and MPI?

- OpenMP
  - language extension, requires compiler support
  - data transfer happens implicitly through shared memory
  - restricted to shared memory parallelism
  - incremental parallelization
- MPI
  - library, hence fully compiler-independent
  - data transfer requires explicit message passing
  - supports distributed memory parallelism
  - no incremental parallelization

often: both (*"hybrid"* parallelism)!

Execution Model

- fork-join parallelism
  - program starts sequentially
  - parallel regions can be opened, which spawn new threads
  - end of parallel regions synchronize threads
  - afterwards, execution continues sequentially

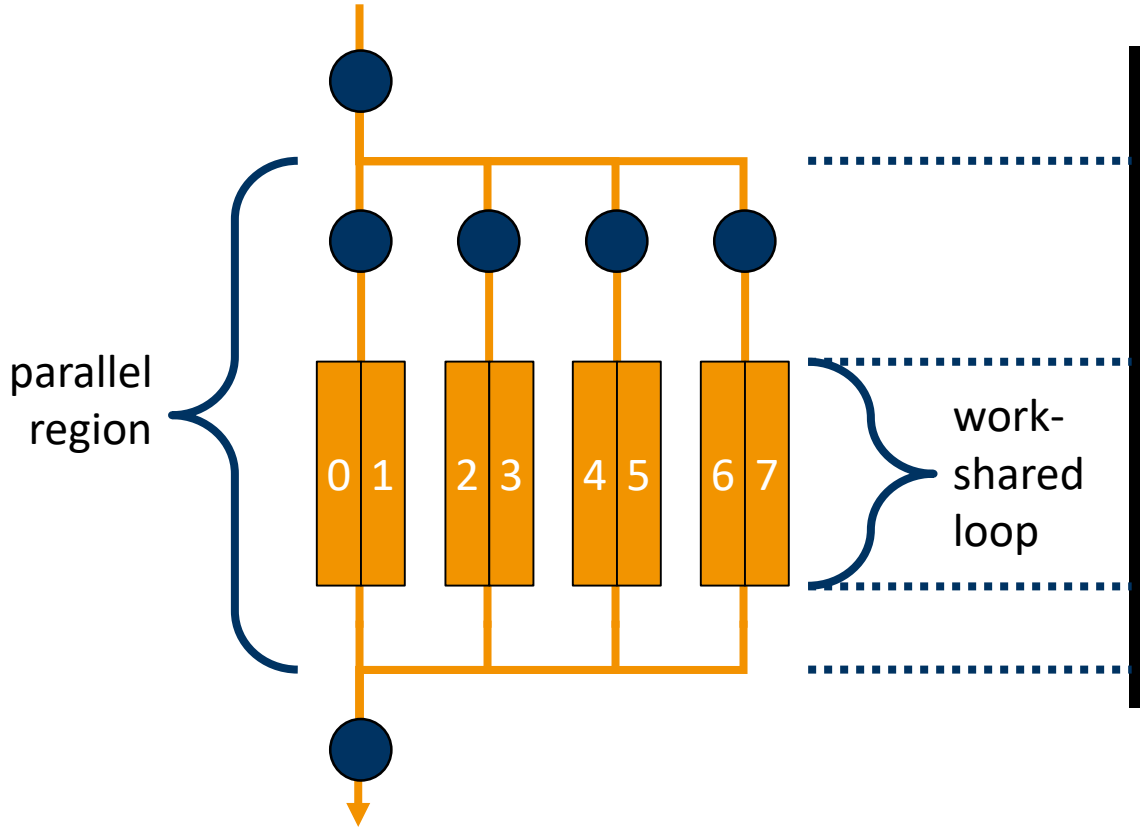


Programming Model

- mark code regions with directives or *pragmas*, e.g.
  - parallel / sequential regions
  - work to be distributed
  - thread synchronization
- add *clauses* for further information, e.g.
  - which variables to share, which not to
  - scheduling strategies
  - forced execution order
- any valid OpenMP program must be a valid sequential program if all pragmas are removed!

```
int f = ...
#pragma omp parallel shared(a,b,c,f)
  default(none)
{
  #pragma omp for
  for(int i = 0; i < 8; ++i) {
    c[i] = a[i] + b[i] * f;
  }
}
```

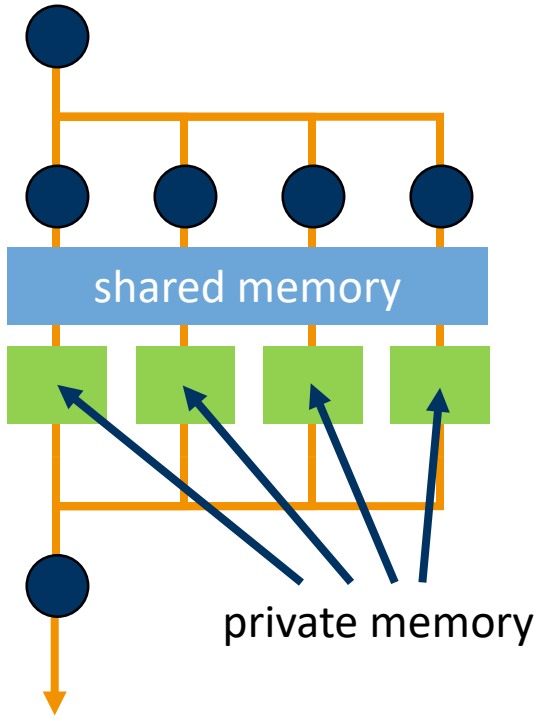
Programming Model cont'd




```
int f = ...
#pragma omp parallel shared(a,b,c,f)
  default(none)
{
  #pragma omp for
  for(int i = 0; i < 8; ++i) {
    c[i] = a[i] + b[i] * f;
  }
}
```

Memory Model

- OpenMP is based on threads
  - all threads have access to global, shared data
  - each thread has additional local, private data
  - modifications to private data are not visible across threads
  - modifications to shared data are not necessarily immediately visible across threads



Compilation and Execution

- compile as usual but include OpenMP-specific flag
  - e.g. gcc/clang/ARM: `-fopenmp`, Intel: `-qopenmp`, IBM: `-qsmp=omp`
- execute as usual, but set required environment variables
  - e.g. `OMP_NUM_THREADS` for controlling degree of parallelism
- be sure to properly set up your job submission
  - e.g. for SGE @ LCC2, use `-pe openmp`

OpenMP API

OpenMP API cont'd

- pragmas
  - control constructs
    - parallelism & work sharing
  - data sharing
    - private & shared variables, initialization
  - synchronization
    - critical & atomic sections, barriers
- library functions
  - querying/controlling environment
  - timing
  - locking
- environment variables
  - degree and nesting of parallelism
  - loop scheduling
  - thread mapping and binding

Pragmas

- `#pragma omp` *`directive`* `[` *`clause`* `[, clause ] ]` *`(newline)`*
- pragmas must be on their own source code line and end with a newline
- OpenMP directives can often take a number of optional clauses, possibly with parameters
- pragmas have dynamic and lexical extent
  - e.g. `#pragma omp for` must always be nested in `#pragma omp parallel`
  - but not necessarily statically (see example on the right)

```
void bar() {
    #pragma omp for
    for(...) { ... }
}

void foo() {
    #pragma omp parallel
    bar();
}
```

Combined Pragmas

```
int f = ...
#pragma omp parallel shared(a,b,c,f)
  default(none)
{
  #pragma omp for
  for(int i = 0; i < 8; ++i) {
    c[i] = a[i] + b[i] * f;
  }
}
```

```
int f = ...
#pragma omp parallel for shared(a,b,c,f)
  default(none)
for(int i = 0; i < 8; ++i) {
  c[i] = a[i] + b[i] * f;
}
```

Library Functions

- querying/controlling environment
  - `omp_get_num_threads()`
  - `omp_get_thread_num()`
  - `omp_get_nested()`
  - `omp_in_parallel()`
  - and a few others, also setters!
- timing
  - `omp_get_wtime()`
  - `omp_get_wtick()`
- locking
  - `omp_init_lock()`
  - `omp_set_lock()`
  - `omp_unset_lock()`
  - `omp_test_lock()`
  - `omp_destroy_lock()`

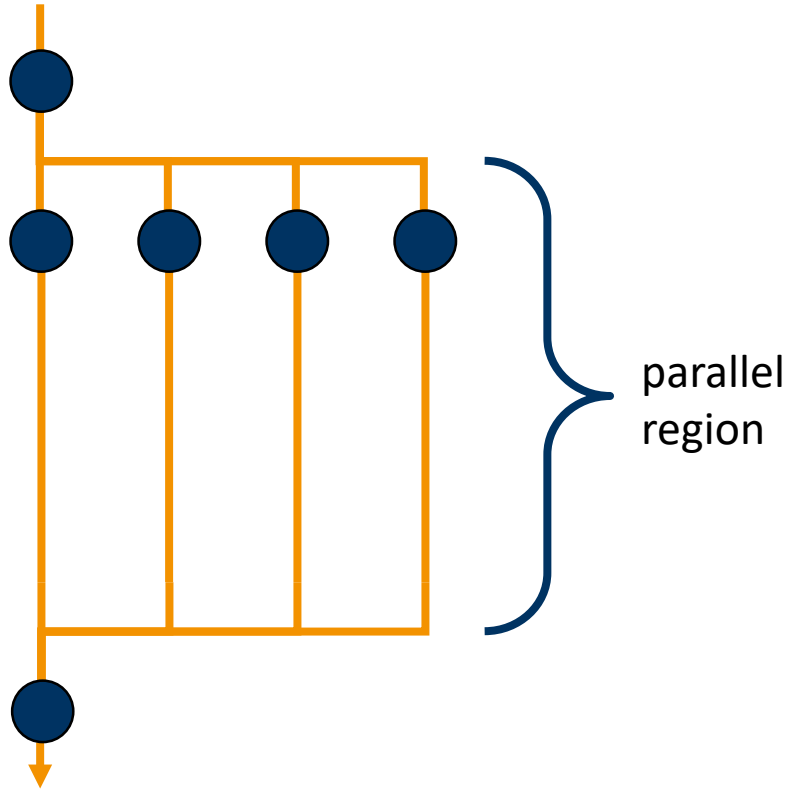
Environment Variables

- OMP_NUM_THREADS
  - sets the number of threads during execution of parallel regions
  - if dynamic adjustment is enabled, sets the maximum number of threads
  - default is implementation-defined
- OMP_SCHEDULE
  - applies to `for` work sharing only
  - supports `static`, `dynamic`, and `guided` with optional chunk size
  - e.g. `OMP_SCHEDULE=static,4`
- OMP_NESTED
  - enables/disables nested parallelism
- OMP_PROC_BIND
  - enables/disables thread binding
- OMP_PLACES
  - controls mapping threads to hardware resources (e.g. cores or sockets)

`parallel` Directive

- `#pragma omp parallel`
  - must be followed by a single-entry single-exit statement or an OpenMP construct
  - master thread creates a team of threads, each executing the same code redundantly
  - implicit barrier at the end (threads in team synchronize), only master continues

- `parallel` may also be nested
  - but with great power comes great responsibility…



Hello World in OpenMP

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

int main(int argc, char** argv) {
  #pragma omp parallel
  {
    int myThreadID = omp_get_thread_num();
    int numThreads = omp_get_num_threads();
    printf("Hello from thread %d of %d\n",
      myThreadID, numThreads);
  }
  return 0;
}
```

```
$ OMP_NUM_THREADS=4 ./hello
Hello from thread 0 of 4
Hello from thread 1 of 4
Hello from thread 3 of 4
Hello from thread 2 of 4
```

Data Sharing Clauses

- `private`
  - each thread gets a private copy of variable, no longer *"storage-associated"* with original variable
  - private copy is not initialized
  - default for variables declared inside parallel region
  - often better to declare variables inside parallel region, reduces amount of code (also minimizes *"vertical distance"* in source code)

- `shared`
  - each thread references the same, global copy
  - data races if access is not synchronized
  - default for variables declared outside parallel region and global variables, often used for read-only access

- `default`
  - can be set to `shared`, or `none` for C/C++
  - `none` helpful for detecting missing variables in clauses (compiler will complain!)

Data Sharing Clauses cont'd

```
int f = ...
#pragma omp parallel shared(a,b,c,f)
  default(none)
{
  #pragma omp for
  for(int i = 0; i < 8; ++i) {
    c[i] = a[i] + b[i] * f;
  }
}
```

```
int f = ...
#pragma omp parallel
{
  #pragma omp for
  for(int i = 0; i < 8; ++i) {
    c[i] = a[i] + b[i] * f;
  }
}
```

Data Sharing Clauses cont'd

- `firstprivate`
  - like `private`, but private copies are initialized with value of copy outside of parallel region
- `lastprivate`
  - like `private`, but outside copy is set to the private copy of the final iteration (`for` loops) or last section (`sections`), **NOT** the iteration/section that was chronologically executed last
- `threadprivate`
  - like private, but will persist across parallel regions
  - master thread variable is storage-associated with original variable (not the case for `private`!)

`reduction` Clause

- performs reduction to a single variable in parallel or loop context
  - arithmetic ops: `+`, `-`, `*`, `max`, `min`
  - logical ops: &, &&, |, ||, ^
  - same issues as with MPI regarding associativity of operations!
- user-defined reductions are possible
  - need to be declared with `#pragma omp declare reduction`

```
#pragma omp parallel
{
  #pragma omp for reduction(+:x)
  for(int  i = 0; i < 10; ++i) {
    x += i;
  }
}

// or

#pragma omp parallel reduction(-:x)
x -= omp_get_thread_num();
```

Work Sharing

Work Sharing Directives

- distribute execution of following code region among existing threads of the team
- must be enclosed in parallel region
- cannot be directly nested
- do not launch new threads
- no barrier on entry
- implicit barrier on exit
  - unless `nowait` clause

- `for`
- `sections`
- `single`
- `task`
- `simd`

`for` Directive

- loop iterations may be executed in parallel
  - requires loop iterations to be independent (dependence analysis)
  - matches SPMD patterns / data parallelism
  - arbitrary thread / iteration mapping
- (still) most common form of data parallelism in OpenMP
- can also take clauses
  - `reduction`
  - `schedule`
  - `collapse`

```
#pragma omp parallel
{
  #pragma omp for
  for(/*init*/; /*test*/; /*inc*/) {
        ...
  }
}
```

`for` Directive cont'd

- `for` loops must have canonical form
  - defined by the OpenMP specification
  - requires number of iterations to be known upon loop entry
    - `init`, `test`, and `inc` expressions must be loop invariant
    - `test` only allows `<`, `<=`, `>`, `>=`
    - `inc` only allows common patterns such as `++var`, `var++`, `--var`, `var--`, `var+=step`, `var-=step`, …
    - loop variable must not be written to in loop body
- C: iterator must be integer or pointer
- C++: iterator must use random access iterators
  - range-based `for` only with OpenMP ≥ 5.0

```
#pragma omp parallel
{
  #pragma omp for
  for(/*init*/; /*test*/; /*inc*/) {
        ...
  }
}
```

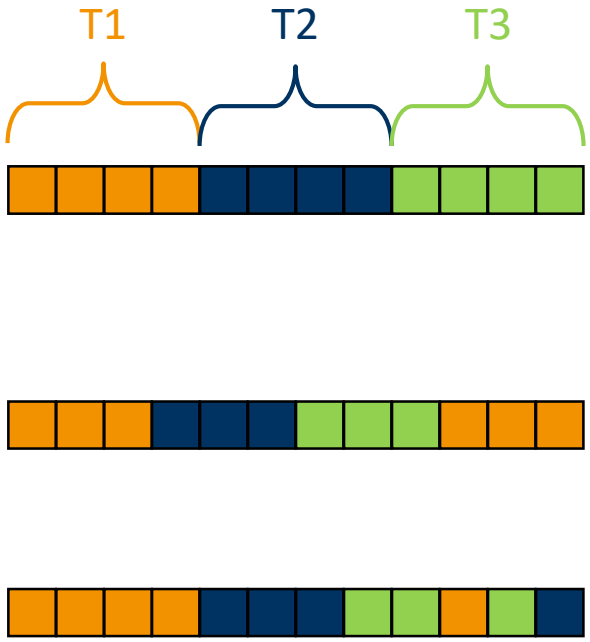
`for`: `schedule` Clause

- specifies method of dividing and assigning chunks
- static: equally-sized chunks, fixed round-robin assignment
  - optional: chunk size (default is “approximately equal in size & at most one chunk per thread”)
- dynamic: equally-sized chunks assigned turn-by-turn
  - optional: chunk size (default is 1)
- guided: like dynamic, but chunk size decreases proportionally to no. of unassigned iterations
  - optional: minimum chunk size (default is 1)
- also available: `auto`, `runtime`

```
#pragma omp parallel
{
  #pragma omp for schedule(dynamic,2)
  for(/*init*/; /*test*/; /*inc*/) {
        ...
  }
}
```

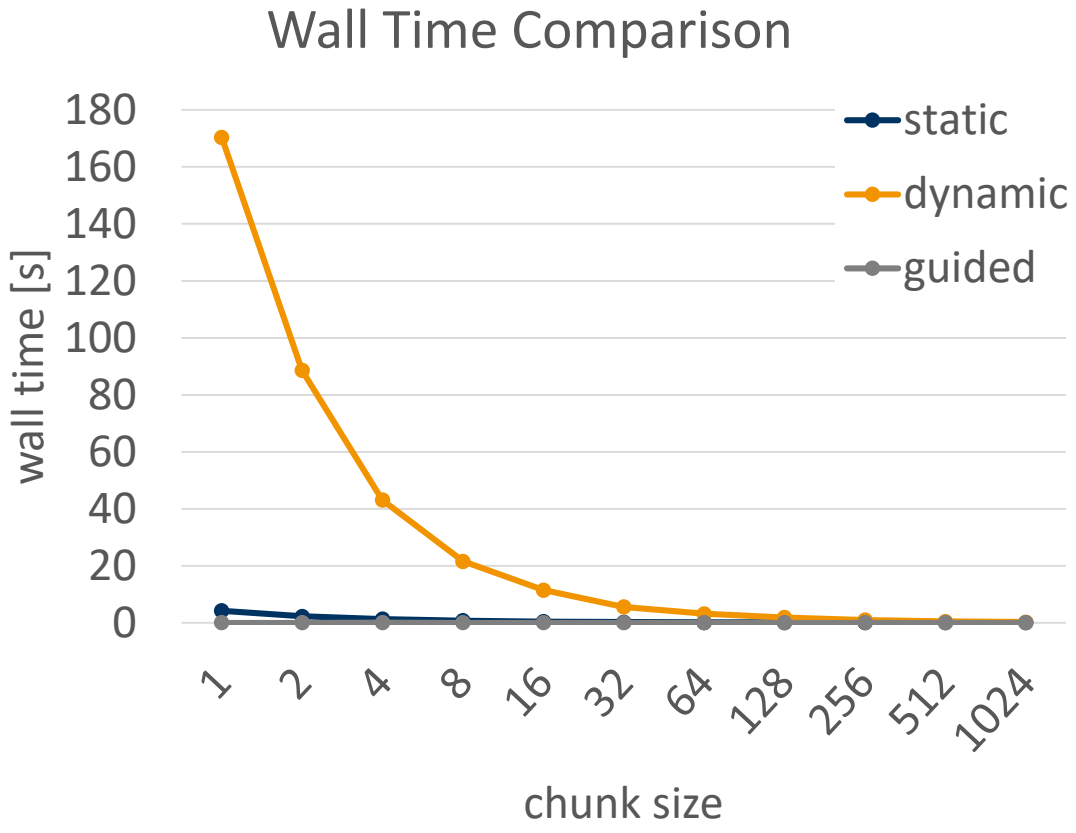
`for`: `schedule` Clause cont'd

- specifies method of dividing and assigning chunks
- static: equally-sized chunks, fixed round-robin assignment
  - optional: chunk size (default is "approximately equal in size & at most one chunk per thread")
- dynamic: equally-sized chunks assigned turn-by-turn
  - optional: chunk size (default is 1)
- guided: like dynamic, but chunk size decreases proportionally to no. of unassigned iterations
  - optional: minimum chunk size (default is 1)
- also available: `auto`, `runtime`



Comparing OpenMP Loop Scheduling Strategies

- incrementing a 64 bit integer in 10^{11} loop iterations on LCC2, gcc 8.2.0, 8 threads
- static, dynamic and guided loop scheduling for increasing chunk sizes 2^n with $0 \leq n \leq 10$



`for`: `collapse` Clause

- given a loop nest, the goal is usually to parallelize and distribute the outermost loop
  - minimizes overhead
- What if the outermost loop has low iteration count?
  - insufficient parallelism for modern systems
- `collapse` combines multiple iteration spaces into a single, larger one
  - allows to exploit more parallelism

```
#pragma omp parallel for collapse(3)
for(int i = 0; i < 3; ++i) {
  for(int j = 0; j < 4; ++j) {
    for(int k = 0; k < 5; ++k) {
      ...
    }
  }
}
```

`sections` Directive

- sections may be executed concurrently, each by an arbitrary thread of the team
- matches MPMD patterns
- easily leads to load imbalance if individual sections not equally work-intensive
  - also, maximum degree of parallelism limited by number of sections

```
#pragma omp parallel
{
  #pragma omp sections
  {
    #pragma omp section
    { ... }
    #pragma omp section
    { ... }
    #pragma omp section
    { ... }
  }
}
```

`single` Directive

- code region will only be executed by a single, arbitrary thread
- implicit barrier at the end for all threads in the team
- also available as `master` variant
  - like single, but for master thread
  - no implicit barrier at the end

```
#pragma omp parallel
{
  #pragma omp single
  {
    ...
  }
}
```

Synchronization

Synchronization Directives

- constructs discussed so far are fairly high-level in terms of synchronization
  - e.g. unable to enforce specific order or simply wait for all threads
- OpenMP also offers more fine-grained synchronization directives
  - `barrier`
  - `critical`
  - `atomic`
  - `ordered`
  - `flush`
  - `master`

`barrier` Directive

- explicit barrier requested by user
- threads are not allowed to continue until all have reached the barrier

```
#pragma omp parallel
{
  ...
  #pragma omp barrier
  ...
}
```

`critical` Directive

- code region executed by all threads but only one at a time
- can be named to allow finer-grained mutual exclusion
  - only critical regions with the same name enforce mutual exclusion
  - all regions without a name have the same name

```
#pragma omp parallel
{
  #pragma omp critical(foo)
  { ... }
  #pragma omp critical(foo)
  { ... }
  #pragma omp critical(bar)
  { ... }
  #pragma omp critical
  { ... }
  #pragma omp critical
  { ... }
}
```

`atomic` Directive

- same as `critical`, but restricted to a single memory location and certain operations
- restriction allows mapping to fast hardware mechanisms
  - optional specialization clauses `read`, `write`, `update`, and `capture`
- keeps code hardware- and compiler-independent compared to using intrinsics
  - but may just be a wrapper for `critical` e.g. when lacking hardware support

```
int count = 0;
#pragma omp parallel
{
    #pragma omp atomic
    count++;
}
```

`ordered` Directive + Clause

- enforces critical region with sequential execution order
- required for strong sequential equivalence
  - but at high performance cost
- only efficient if code outside the ordered region is expensive enough
  - remember guidelines about strong / weak sequential equivalence
  - check whether your numerical method really needs strong sequential equivalence

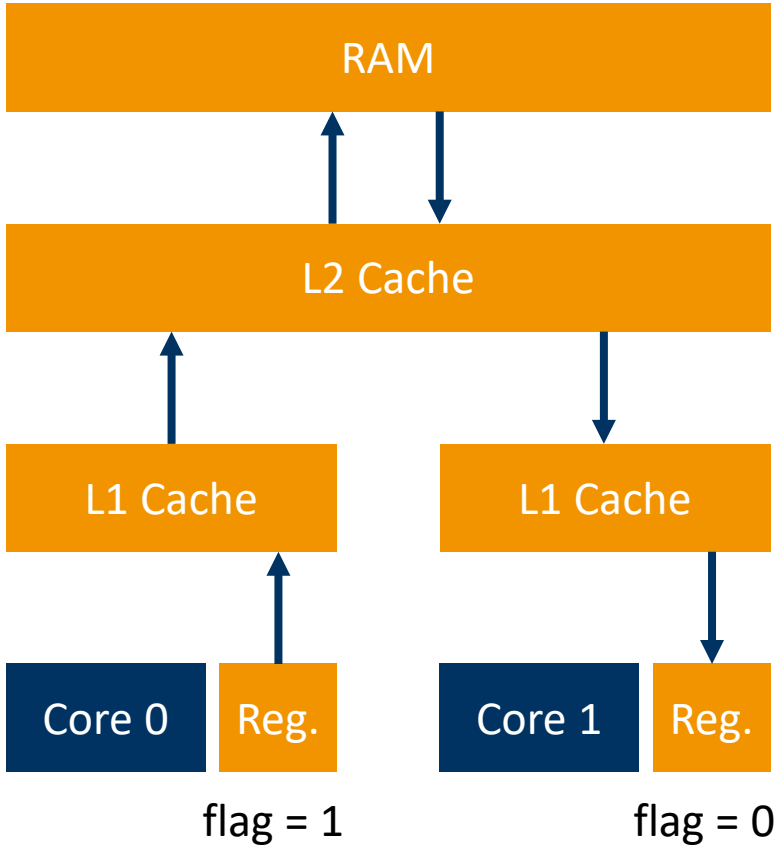
```
double total = 0.0;
#pragma omp parallel for ordered
for(int i = 0; i < N; ++i) {
    double part = f(i);
    #pragma omp ordered
    total += part;
}
```

`flush` Directive

- problem: writes by one thread are not immediately visible to another in the same parallel region without synchronization
- example on the right: the second section could hang in while loop
  - But why?

```
#pragma omp parallel sections
{
    #pragma omp section
    { // producer section
        // produce some data
        flag = 1;
    }
    #pragma omp section
    { // consumer section
        while (flag == 0) { }
        // use data
    }
}
```

`flush` Directive cont'd




```
#pragma omp parallel sections
{
    #pragma omp section
    { // producer section
        // produce some data
        flag = 1;
    }
    #pragma omp section
    { // consumer section
        while (flag == 0) { }
        // use data
    }
}
```

`flush` Directive cont'd

```
#pragma omp parallel sections
{
  #pragma omp section
  { // producer section
    // produce and flush data
    #pragma omp flush
    #pragma omp atomic write
    flag = 1;
    #pragma omp flush(flag)
  }
```

```
  #pragma omp section
  { // consumer section
    while (1) {
      #pragma omp flush(flag)
      #pragma omp atomic read
      int temp_flag = flag;
      if(temp_flag == 1) break;
    }
    // use data
  }
} // end sections
```

`flush` Directive cont'd

- `flush` is implied at
  - `barrier`
  - entry and exit of `critical`
  - exit of
    - `parallel`
    - `for`
    - `sections`
    - `single`
  - set/unset of locks

- if otherwise required, use `flush` directive explicitly

Tales From the Proseminar

Tales From the Proseminar

- Which code version is faster? (yes, both have a race condition…)

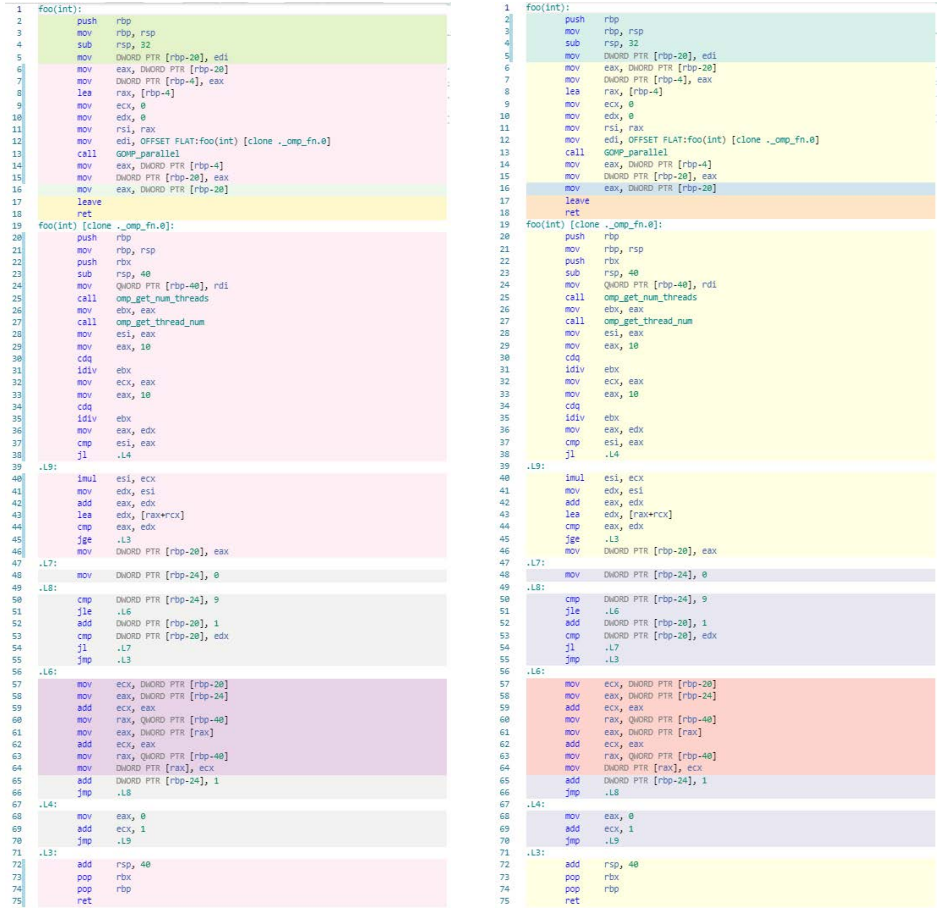
```
int foo(int dummy) {
    int i, j;
    #pragma omp parallel for private(j)
    for(i = 0; i < 10; ++i) {
        for(j = 0; j < 10; ++j) {
            dummy += i + j;
        }
    }
    return dummy;
}
```

```
int foo(int dummy) {
    #pragma omp parallel for
    for(int i = 0; i < 10; ++i) {
        for(int j = 0; j < 10; ++j) {
            dummy += i + j;
        }
    }
    return dummy;
}
```

Tales From the Proseminar

- the assembly code is exactly the same
  - screenshot shows output for gcc 9.2 and -O0 (also works for -O3)

- https://godbolt.org/z/SKx8hA



```
foo(int):
        push    rbp
        mov     rbp, rsp
        sub     rsp, 32
        mov     DWORD PTR [rbp-20], edi
        mov     eax, DWORD PTR [rbp-20]
        mov     DWORD PTR [rbp-4], eax
        lea     rax, [rbp-4]
        mov     ecx, 0
        mov     edx, 0
        mov     rsi, rax
        mov     edi, OFFSET FLAT:foo(int) [clone ._omp_fn.0]
        call    GOMP_parallel
        mov     eax, DWORD PTR [rbp-4]
        mov     DWORD PTR [rbp-20], eax
        mov     eax, DWORD PTR [rbp-20]
        leave
        ret
foo(int) [clone ._omp_fn.0]:
        push    rbp
        mov     rbp, rsp
        push    rbx
        sub     rsp, 40
        mov     QWORD PTR [rbp-40], rdi
        call    omp_get_num_threads
        mov     ebx, eax
        call    omp_get_thread_num
        mov     esi, eax
        mov     eax, 10
        cdq
        idiv    ebx
        mov     ecx, eax
        mov     eax, 10
        cdq
        idiv    ebx
        mov     eax, edx
        cmp     esi, eax
        jl      .L4
.L9:
        imul    esi, ecx
        mov     edx, esi
        add     eax, edx
        lea     edx, [rax+rcx]
        cmp     eax, edx
        jge     .L3
        mov     DWORD PTR [rbp-20], eax
.L7:
        mov     DWORD PTR [rbp-24], 0
.L8:
        cmp     DWORD PTR [rbp-24], 9
        jle     .L6
        add     DWORD PTR [rbp-20], 1
        cmp     DWORD PTR [rbp-20], edx
        jl      .L7
        jmp     .L3
.L6:
        mov     ecx, DWORD PTR [rbp-20]
        mov     eax, DWORD PTR [rbp-24]
        add     ecx, eax
        mov     rax, QWORD PTR [rbp-40]
        mov     eax, DWORD PTR [rax]
        add     ecx, eax
        mov     rax, QWORD PTR [rbp-40]
        mov     DWORD PTR [rax], ecx
        add     DWORD PTR [rbp-24], 1
        jmp     .L8
.L4:
        mov     eax, 0
        add     ecx, 1
        jmp     .L9
.L3:
        add     rsp, 40
        pop     rbx
        pop     rbp
        ret
```

Summary

- main characteristics
  - incremental parallelization
- programming, execution and memory models
  - based on threads and shared data access
  - mainly relies on pragmas as programmer interface
- directives
  - parallelism, work sharing, data sharing, synchronization
- Tales From the Proseminar
  - minimize vertical code distance
  - specifically: declare `for` loop iterators in loop header whenever possible

Image Sources

- Helen Lovejoy: https://simpsons.fandom.com/wiki/Helen_Lovejoy