Introduction to Parallel Programming

Part II: Shared Memory

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Outline

Resources

Resources I

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OpenMP: Standards and specifications

- Dagum and Menon 1998; Duran et al. 2011; Ayguade et al. 2009
- Useful books: *Using OpenMP* [Chapman, Jost, and Van Der Pas 2008]
- `http://www.openmp.org`

Other Parallel Programming Models

- PGAS: `http://www.pgas.org`
- Accelerator programming:
  - Cuda: `https://developer.nvidia.com/cuda-zone`
  - OpenCL: `https://www.khronos.org`, in particular `https://www.khronos.org/opencl/`
  - OpenACC: `https://www.openacc.org`
    - This is Nvidia's version of OpenMP for their GPU cards
    - OpenMP 4 provides keywords for accelerators, but it is clearly biased in favor of the (now defunct) Xeon Phi accelerator.

Resources II

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Available implementations

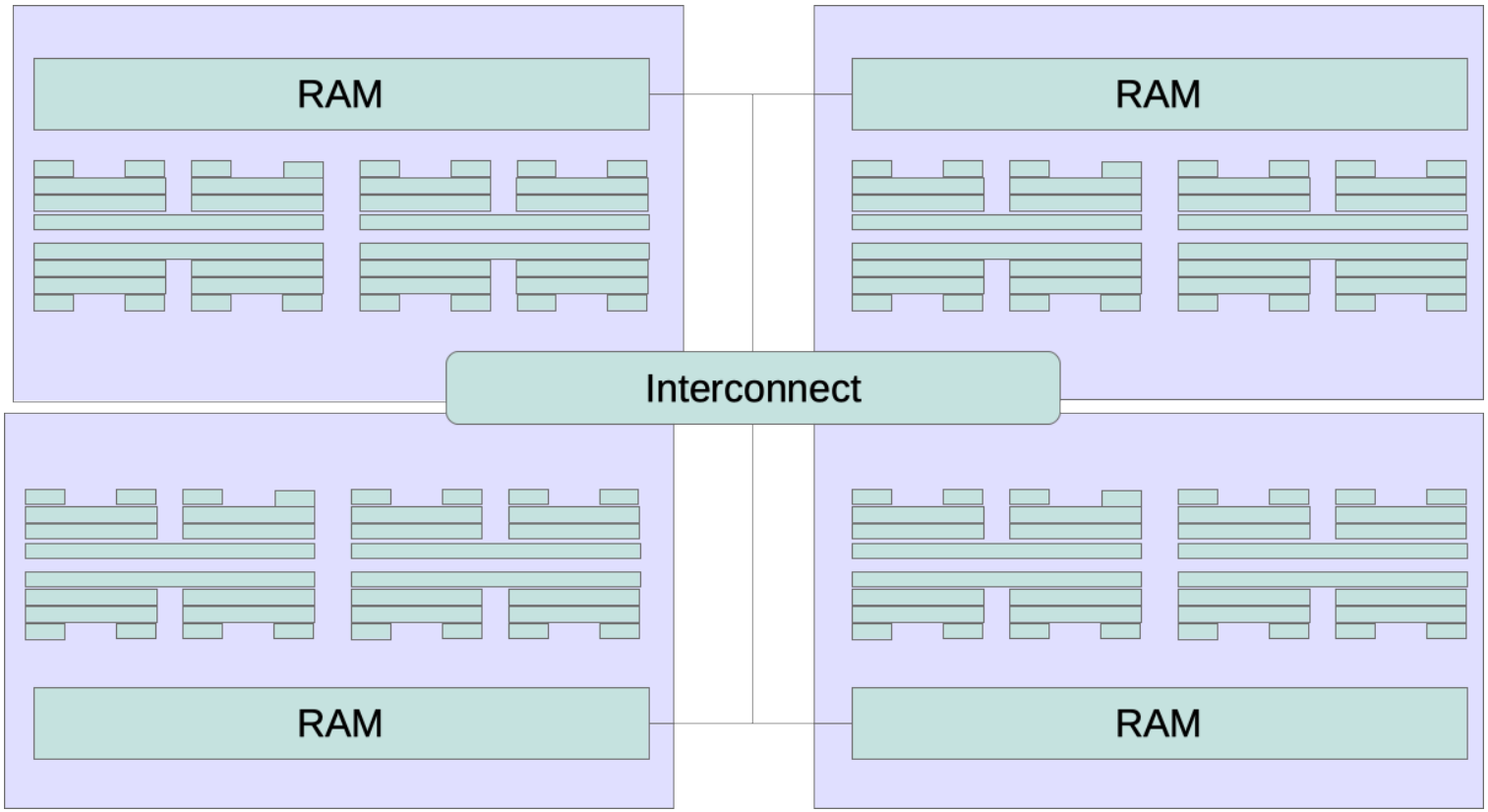
- OpenMP: Clang, GCC since v4.2 (proprietary implementations include Intel's ICC, IBM XL C; *etc.*)
  - Note: GCC's OpenMP runtime is more of a reference implementation than anything.
  - Intel's runtime implementation of OpenMP is free software, and used by Clang. You can also download it and link it to GCC.
- OpenACC: GCC since v5 (the proprietary PGI compiler also implements it)
- OpenCL: `libclc` on LLVM (Clang/LLVM)

Introduction to Shared Memory Parallel Programming

Parallel Architectures I
NUMA

- NUMA (non-uniform memory access) architectures
- Links several SMPs (symmetric multiprocessors)
- Coherence not maintained

Parallel Architectures II
NUMA

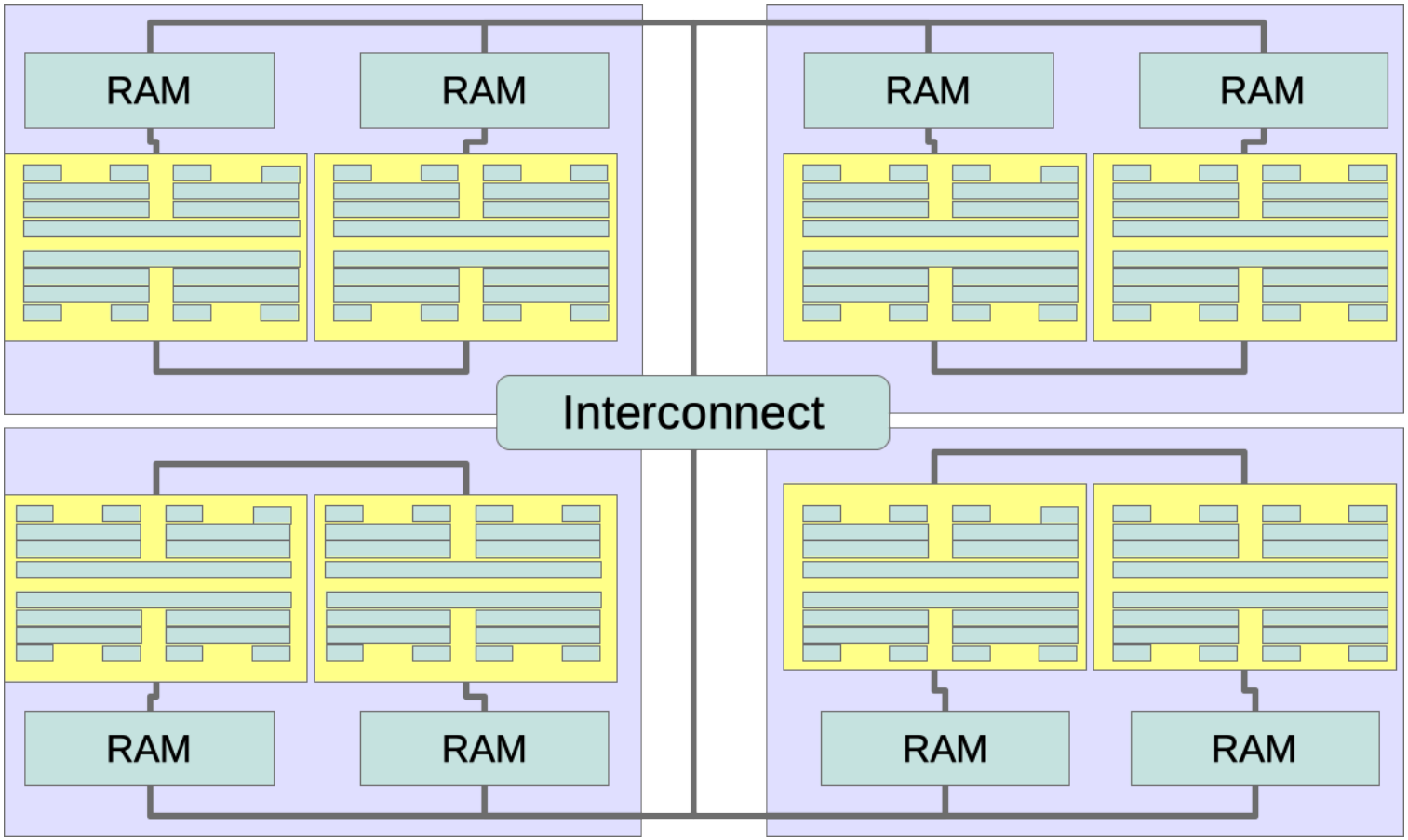


Parallel Architectures I
cc-NUMA

- cc-NUMA (cache-coherent non-uniform memory access) architectures
- Communication between cache controllers to maintain coherence
- Consistent memory image

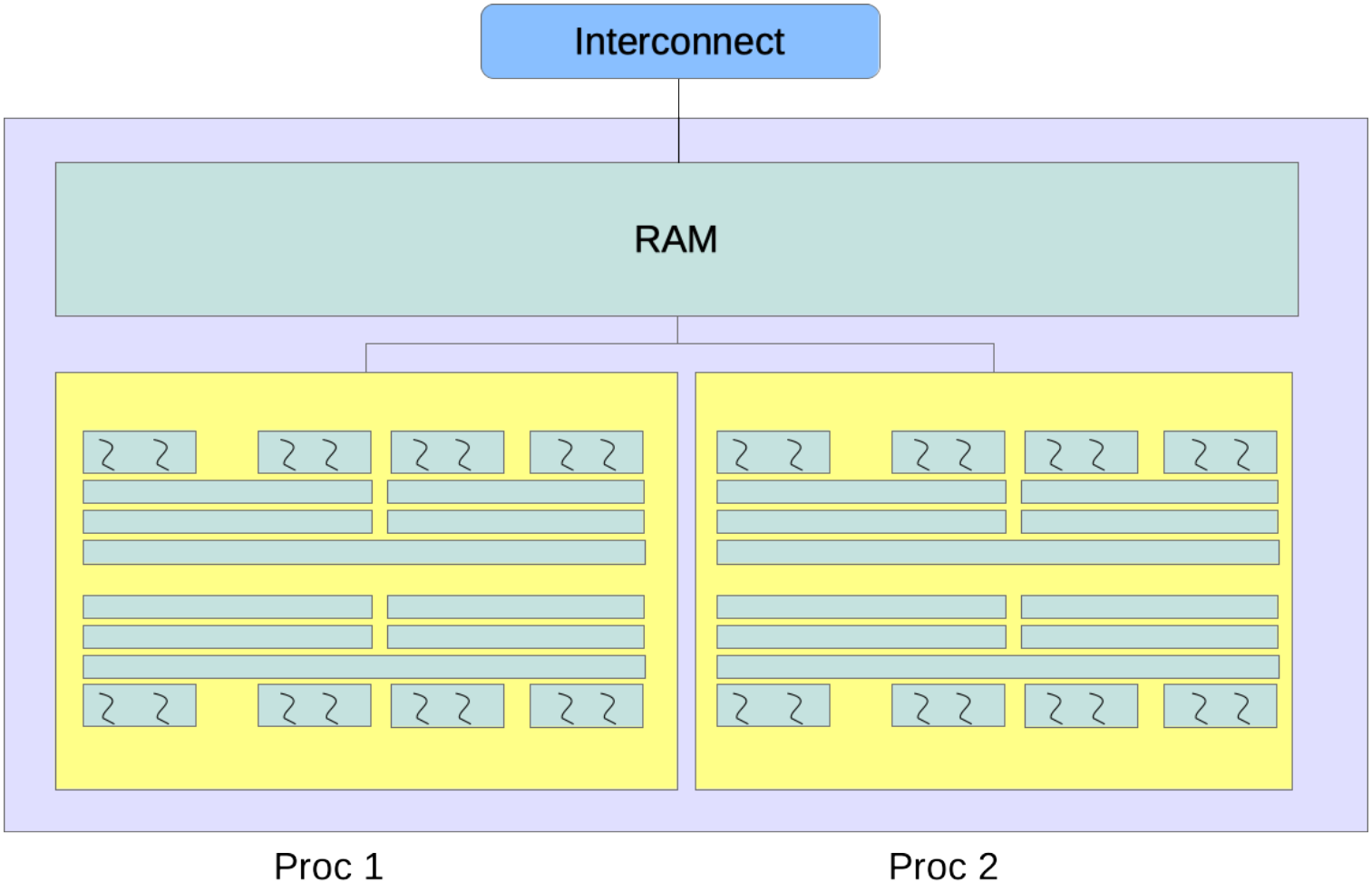
Parallel Architectures II

cc-NUMA



Parallel Architectures

NUMA Node – SMP Architecture



Programming and Execution Models

Message Passing with MPI

- Message Passing Interface (MPI) is the most popular
- Explicit model – message sending/receiving for:
  - Data exchange
  - Synchronization
  - Communication
- Program mer should express parallelism explicitly
- MPI subroutines used at source level
- The *de facto* industry standard for message passing

Programming and Execution Models I

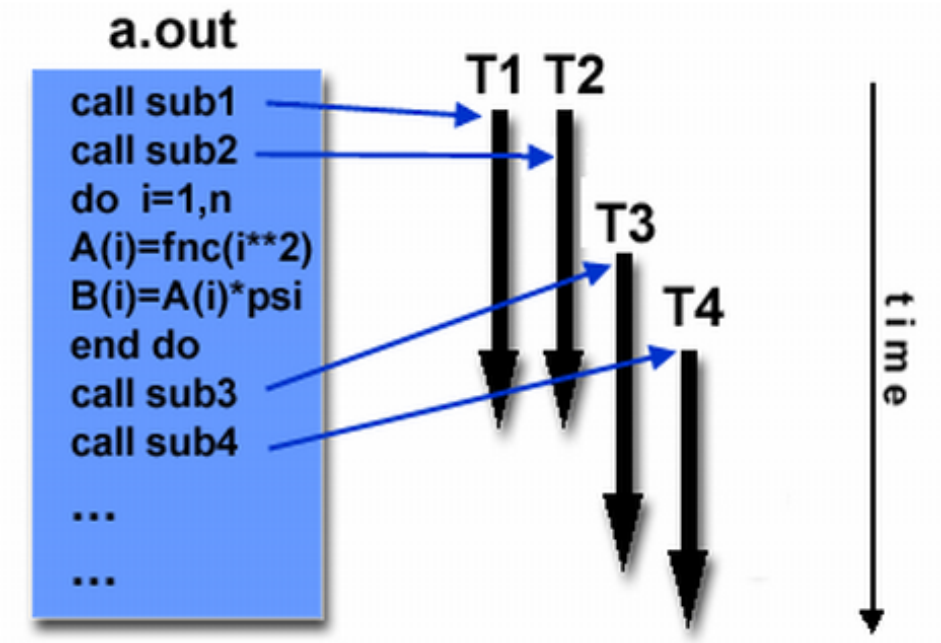
Shared Memory – The Threading Model

Threads

- One program with multiple subroutines
- One cookbook and multiple cooks reading different pages
- Each thread T_i has local data
- Each thread accesses the global memory $\rightarrow$ potential need for synchronization

Programming and Execution Models II

Shared Memory – The Threading Model



Programming and Execution Models I

Shared Memory – The Threading Model Memory Layout

Overview of Threads

- Smallest unit scheduled by the OS
- Different threads belong to one process
- Two types of threads : user-level ("user threads") or kernel-level ("lightweight processes")
- Composed of:
  - A stack
  - A set of registers—*i.e.*, a context

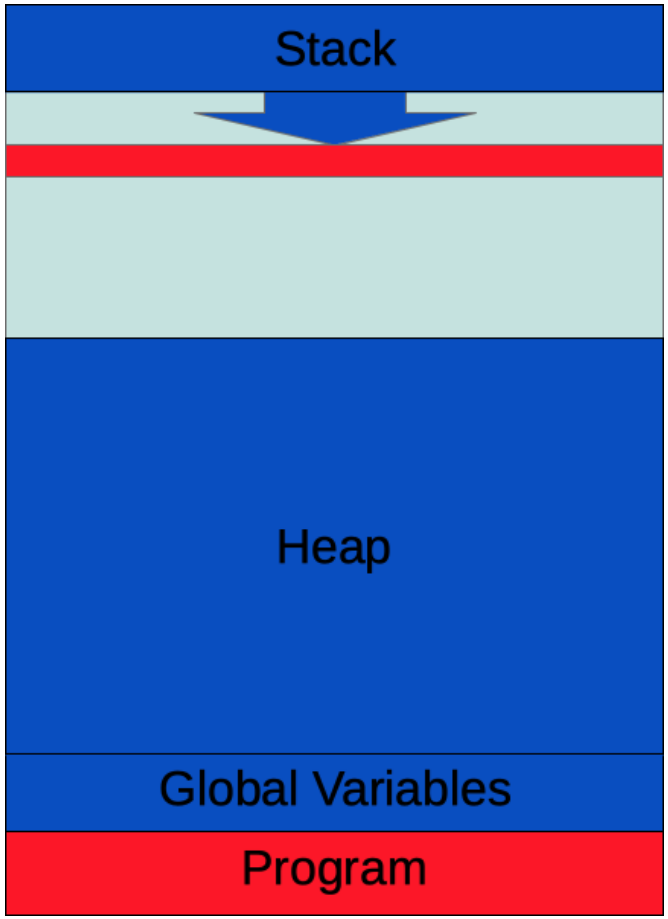


Figure: Single-threaded Process: Memory

Programming and Execution Models II

Shared Memory – The Threading Model Memory Layout

Threads (cont'd)

- Multiple threads share the same address space
- Thread stacks are located in the heap
- A thread's stack size is fixed
  - Except for the master thread ("thread 0")
- Global variables are shared between threads
- Communication between threads is done via the memory

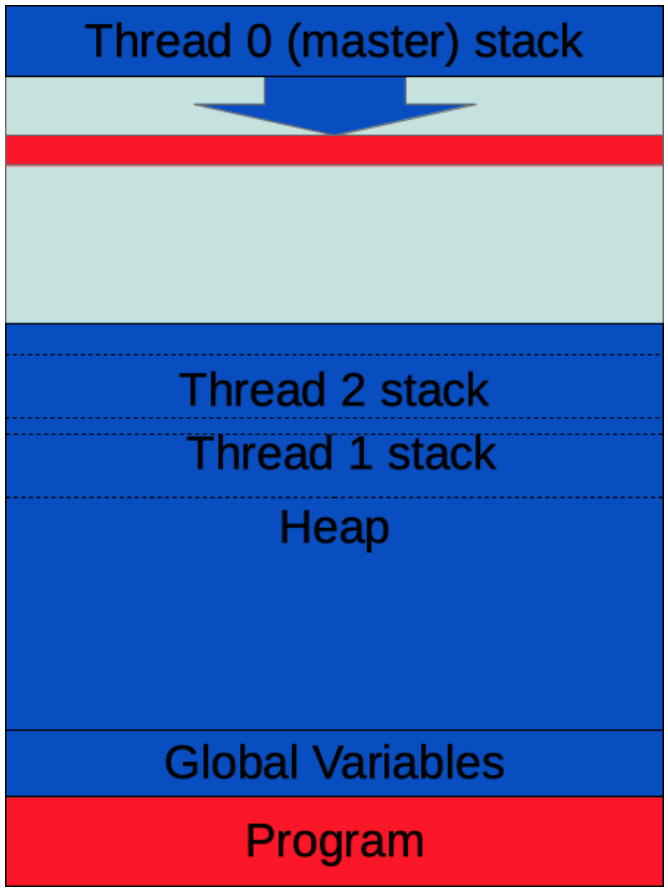


Figure: Multithreaded Process: Memory

Programming and Execution Models III

Shared Memory – The Threading Model Memory Layout

Low-level APIs

- Two main APIs:
  - POSIX threads (PTHREADS): Linux, FreeBSD, MacOS, Solaris, ...
  - Windows Threads
- Different parallel programming models for shared memory:
  - OpenMP
  - Cilk / Cilk++ / CilkPlus
  - Intel Threading Building Blocks (TBB)
  - Chapel / X10 / ...(PGAS languages)

Shared-memory execution models

Introduction to OpenMP I

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The OpenMP Framework

- Stands for Open MultiProcessing
- Three languages supported: C, C++, Fortran
- Supported on multiple platforms: UNIX, Linux, Windows, *etc.*
  - Very portable
- Many compilers provide OpenMP capabilities:
  - The GNU Compiler Collection (gcc) – OpenMP 3.1
  - Intel C/C++ Compiler (icc) – OpenMP 3.1 (and partial support of OpenMP 4.0)
  - Oracle C/C++ – OpenMP 3.1
  - IBM XL C/C++ – OpenMP 3.0
  - Microsoft Visual C++ – OpenMP 2.0
  - *etc.*

Introduction to OpenMP II

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OpenMP's Main Components

- Compiler directives
- A functions library
- Environment variables

The OpenMP Model

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- An OpenMP program is executed using a unique process
- Threads are activated when entering a parallel region
- Each thread executes a task composed of a pool of instructions
- While executing, a variable can be read and written in memory:
  - It can be defined in the stack of a thread: the variable is private
  - It can be stored somewhere in the heap: the variable is shared by all threads

Running OpenMP Programs: Execution Overview

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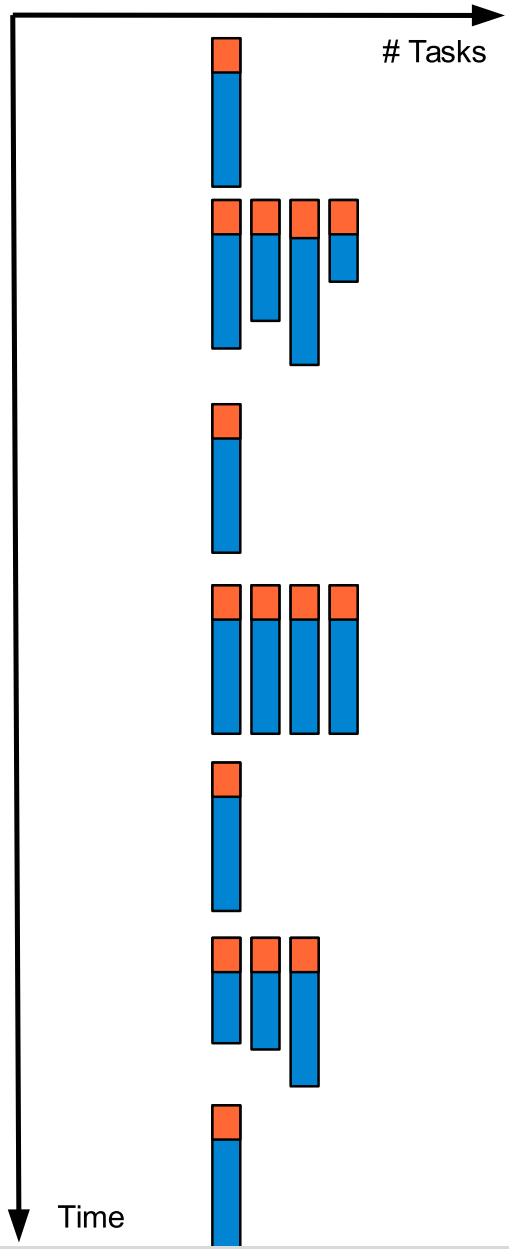
OpenMP: Program Execution

- An OpenMP program is a sequence of serial and parallel regions
- A sequential region is always executed by the master thread: Thread 0
- A parallel region can be executed by multiple tasks at a time
- Tasks can share work contained within the parallel region



Running OpenMP Programs: Execution Overview

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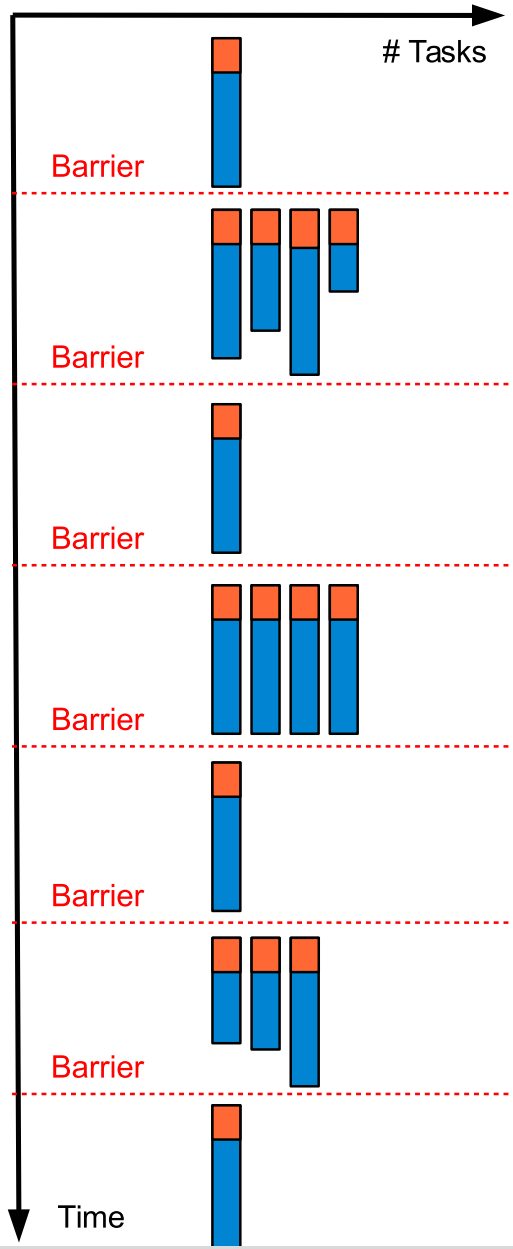

OpenMP Parallel Structures

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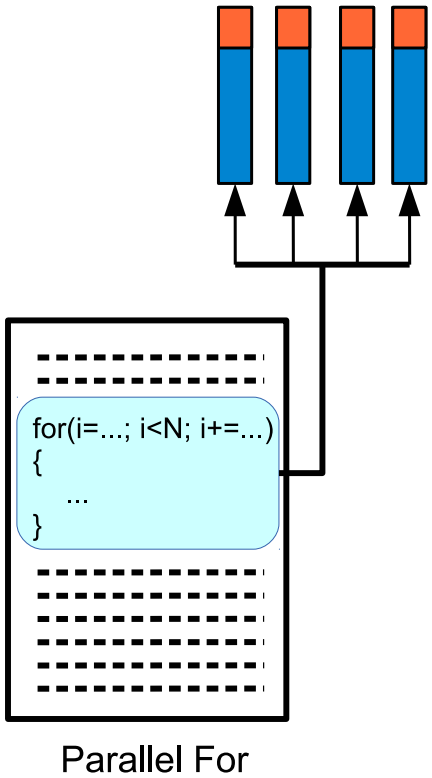
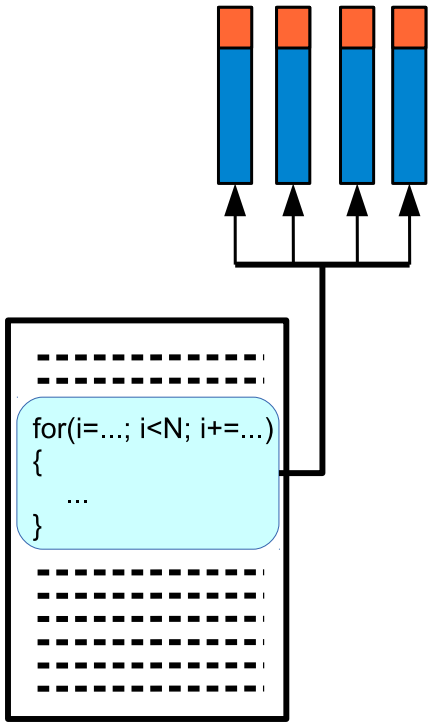
- Parallel loops

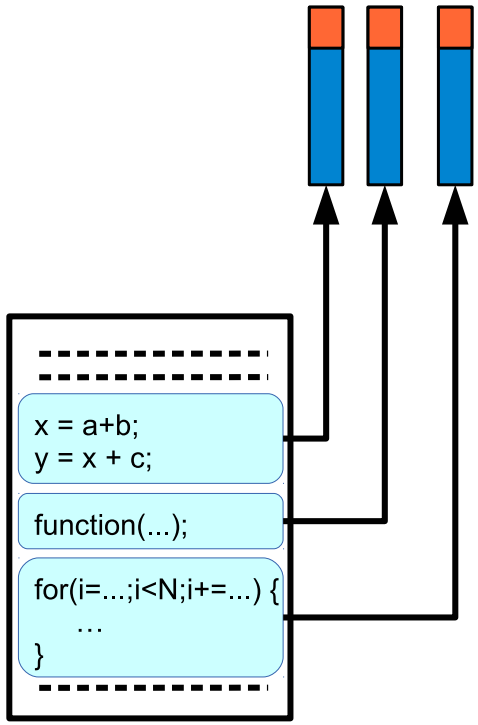


OpenMP Parallel Structures

- Parallel loops
- Sections



Parallel For



Sections

OpenMP Parallel Structures

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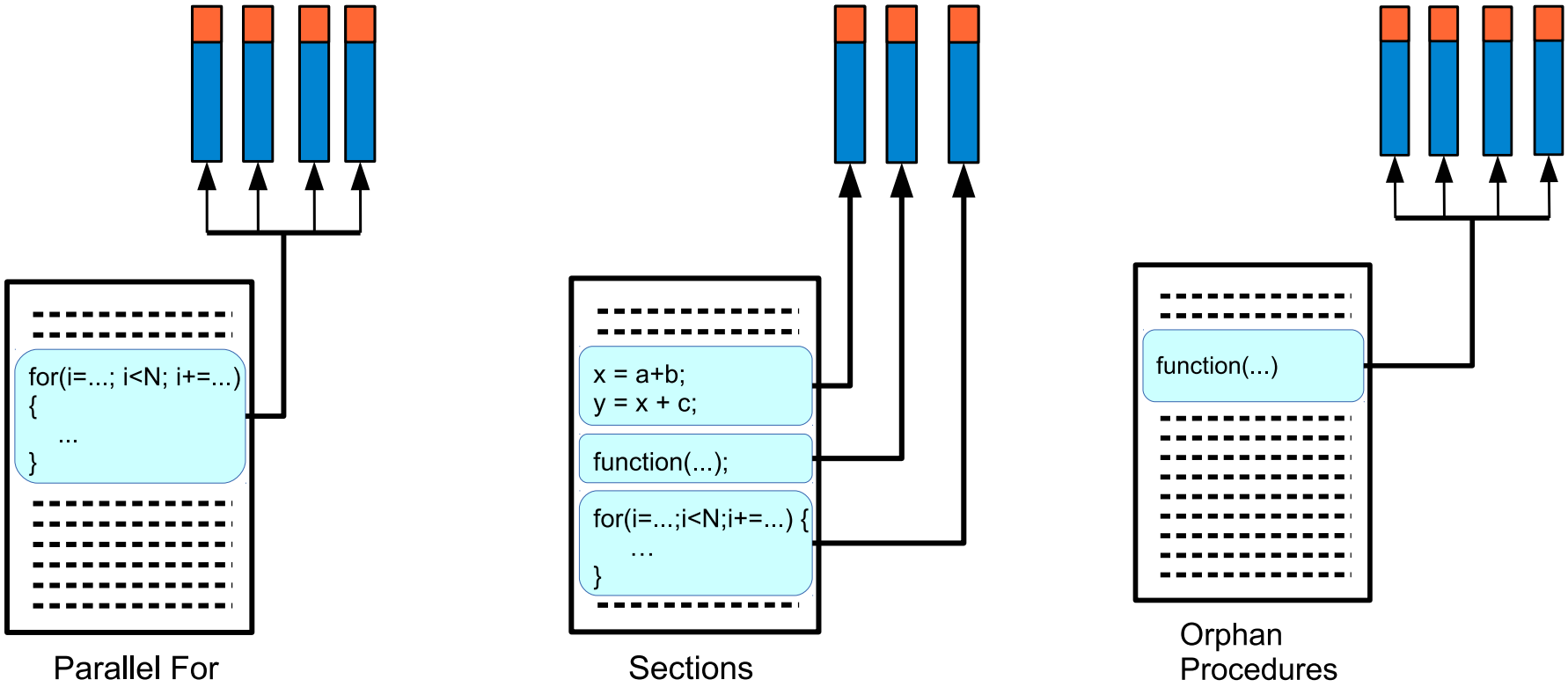
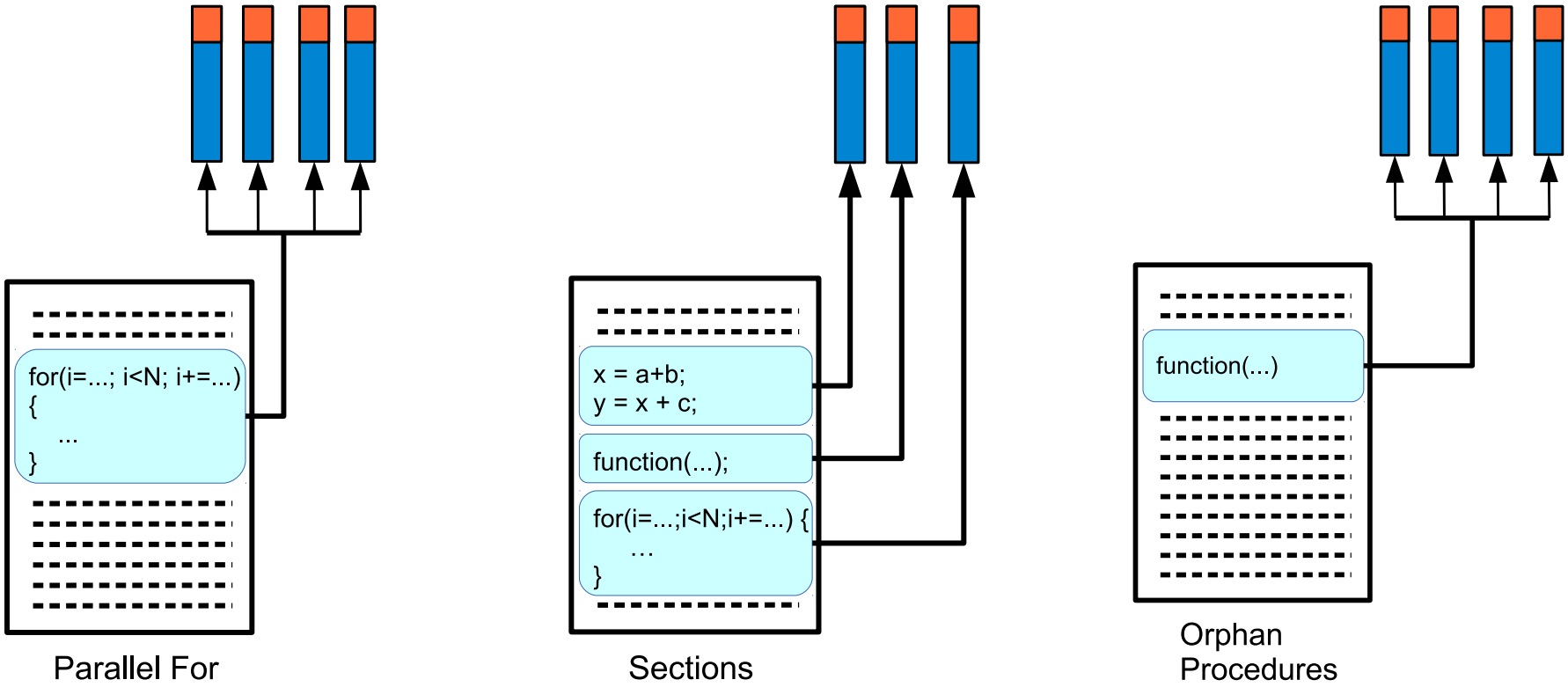
- Parallel loops
- Sections
- Procedures through orphaning



OpenMP Parallel Structures

- Parallel loops
- Sections
- Procedures through orphaning
- Tasks



OpenMP Structure I

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Compilation Directives and Clauses

They define how to:

- Share work
- Synchronize
- Share data

They are processed as comments unless the right compiler option is specified on the command line.

Fonctions and Subroutines

They are part of a library loaded at link time

OpenMP Structure II

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Environment Variables

Once set, their values are taken into account at execution time

OpenMP vs. MPI I

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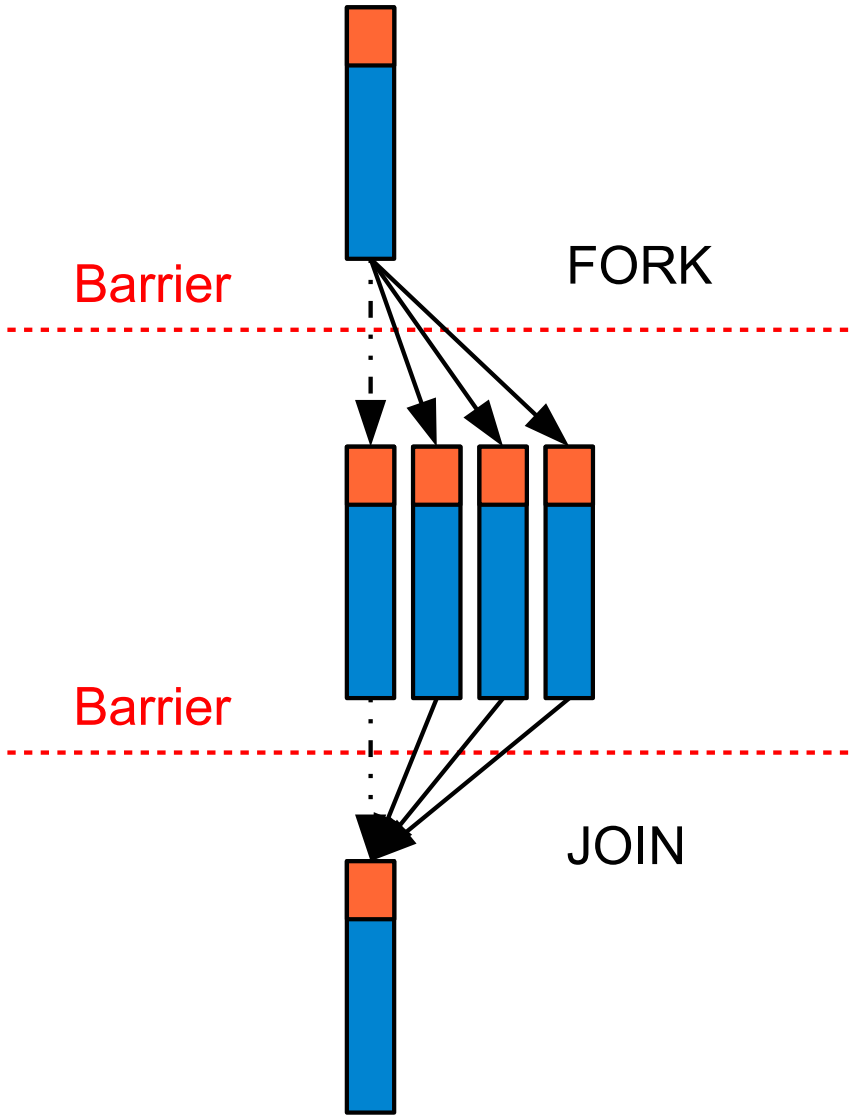
These two programming models are complementary:

- Both OpenMP and MPI can interface using C, C++, and Fortran
- MPI is a multi-process environment whose communication mode is explicit (the user is in charge of handling communications)
- OpenMP is a multi-tasking environment whose communication between tasks is implicit (the compiler is in charge of handling communications)
- In general, MPI is used on multiprocessor machines using distributed memory
- OpenMP is used on multiprocessor machines using shared memory
- On a cluster of independent shared memory machines, combining two levels of parallelism can significantly speed up a parallel program's execution.

OpenMP: Principles

- The developer is in charge of introducing OpenMP directives
- When executing, the OpenMP runtime system builds a parallel region relying on the "fork-join" model
- When entering a parallel region, the master task spawns ("forks") children tasks which disappear or go to sleep when the parallel region ends
- Only the master task remains active after a parallel region is done



Principal Directives I

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Creating a Parallel Region: the `parallel` Directive

```
#pragma omp parallel
{
        /* Parallel region code */
}
```

Principal Directives II

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Data Sharing Clauses

- `shared(...)`: Comma-separated list of all variables that are to be shared by all OpenMP tasks
- `private(...)`: Comma-separated list of all variables that are to be visible only by their task.
  - Variables that are declared private are "duplicated:" their content is unspecified when entering the parallel region, and when leaving the region, the privatized variable retains the content it had *before* entering the parallel region
- `firstprivate(...)`: Comma-separated list of variables whose content must be copied (and not just allocated) when entering the parallel region.
  - The value when leaving the parallel remains the one from before entering it.
- `default(none|shared|private)`: Default policy w.r.t. sharing variables. If not specified, defaults to "shared"

A First Example: Hello World

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```
szuckerm@evans201g:examples$ gcc -std=c99 -Wall -Wextra -pedantic \
                                 -O3 -o omp_hello omp_hello.c
```

```c
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>
#ifndef _OPENMP
#define omp_get_thread_num() 0
#endif

int main(void)
{
    #pragma omp parallel
    {
        int tid = omp_get_thread_num();
        printf("[%d]\tHello, World!\n", tid);
    }

    return EXIT_SUCCESS;
}
```

```
examples$ ./hello
[0] Hello, World!
[3] Hello, World!
[1] Hello, World!
[2] Hello, World!
```

Figure: omp_hello.c

Example: Privatizing Variables

```
examples:$ gcc -std=c99 -Wall -Wextra -pedantic -O3 \
               -o omp_private omp_private.c
omp_private.c: In function ‘main._omp_fn.0’:
omp_private.c:8:11: warning: ‘a’ is used  uninitialized
in this function [-Wuninitialized]
         a = a + 716.;
           ^
omp_private.c:4:11: note: ‘a’ was declared here
     float a = 1900.0;
```

```c
#include <stdio.h>
#include <omp.h>
int  main() {
    float a = 1900.0;
    #pragma omp parallel default(none) private(a)
    {
        a = a + 716.;
        printf("[%d]\ta = %.2f\n",omp_get_thread_num(), a);
    }
    printf("[%d]\ta = %.2f\n",omp_get_thread_num(), a);
    return 0;
}
```

```
[2]  a = 716.00
[1]  a = 716.00
[0]  a = 716.00
[3]  a = 716.00
[0]  a = 1900.00
```

Sharing Data Between Threads

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```
examples:$ gcc -std=c99 -Wall -Wextra -pedantic -O3 \
               -o omp_hello2 omp_hello2.c
```

```c
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>
#ifndef _OPENMP
#define omp_get_thread_num() 0
#endif

int main(void)
{
    int ids[] = {0, 1, 2, 3, 4, 5, 6, 7};
    #pragma omp parallel default(none) shared(ids)
    {
        printf("[%d]\tHello, World!\n", ids[omp_get_thread_num()]);
    }

    return EXIT_SUCCESS;
}
```

```
examples$ ./hello2
[0] Hello, World!
[3] Hello, World!
[1] Hello, World!
[2] Hello, World!
```

Capturing Privatized Variables' Initial Values

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```
szuckerm@evans201g:examples$ gcc -std=c99 -Wall -Wextra -pedantic -O3\
                             -o omp_firstprivate omp_firstprivate.c
```

```c
#include <stdio.h>
#include <omp.h>
int main() {
    float a = 1900.0;

    #pragma omp parallel \
      default(none) firstprivate(a)
    {
        a = a + 716.;
        printf("a = %f\n",a);
    }

    printf("a = %f\n",a);

    return 0;
}
```

```
examples$ ./omp_firstprivate
a = 19716.000000
a = 19716.000000
a = 19716.000000
a = 19716.000000
a = 19000.000000
```

Figure: omp_firstprivate.c

Scope of OpenMP Parallel Regions

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When calling functions from a parallel region, local and automatic variables are implicitly private to each task (they belong to their respective task's stack). Example:

```
#include <stdio.h>
#include <omp.h>
void sub(void);
int main(void) {
    #pragma omp parallel default(shared)
    {
        sub();
    }
    return 0;
}
void sub(void) {
    int a  = 19716;
    a     += omp_get_thread_num();
    printf("a = %d\n", a);
}
```

Parallel Loops

```
szuckerm@evans201g:examples$ gcc -std=c99 -Wall -Wextra -pedantic -O3\
                             -o omp_for parallel_for.c
```

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

int
main(void)
{
    #pragma omp parallel
    {
        int n_threads = omp_get_num_threads();
        #pragma omp for
        for (int i = 0; i < n_threads; ++i) {
            printf("[%d]\tHellow, World!\n", i);
        }
    }
}
```

```
examples$ ./omp_for
[1] Hellow, World!
[0] Hellow, World!
[3] Hellow, World!
[2] Hellow, World!
```

Figure: parallel_for.c

Parallel Loops: A Few Things to Remember

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1. The iterator of a `omp for` loop must use additions/substractions to get to the next iteration (no `i *= 10` in the postcondition)
2. The iterator of the outermost loop (which directly succeeds to the `omp for` directive) is always private, but *not* the ones in other nested loops!
3. There is an implicit barrier at the end of the loop. You can remove it by adding the clause `nowait` on the same line: `#pragma omp for nowait`
4. How the iterations are distributed among threads can be defined using the `schedule` clause.

Parallel Loops I

Specifying the Schedule Mode

The syntax to define a scheduling policy is `schedule(ScheduleType, chunksize)`.
The final line should like this:

```
#pragma omp parallel default(none) \
                    shared(...) private(...) firstprivate(...)
{
    #pragma omp for schedule(...) lastprivate(...)
    for (int i = InitVal; ConditionOn(i); i += Stride)
    { /* loop body */ }
}

// or, all in one directive:

#pragma omp parallel for default(none) shared(...) private(...) \
                         firstprivate(...) lastprivate(...)
    for (int i = InitVal; ConditionOn(i); i += Stride) {
      /* loop body */
    }
```

Parallel Loops II

Specifying the Schedule Mode

The number of iterations in a loop is computed as follows:

$$NumIterations = \left\lfloor \frac{|FinalVal - InitVal|}{Stride} \right\rfloor + |FinalVal - InitVal| \bmod Stride$$

The number of *iteration chunks* is thus computed like this:

$$NumChunks = \left\lfloor \frac{NumIterations}{ChunkSize} \right\rfloor + NumIterations \bmod ChunkSize$$

Parallel Loops III

Specifying the Schedule Mode

Static Scheduling

`schedule(static,chunksize)` distributes the iteration chunks across threads in a round-robin fashion

- Guarantee: if two loops with the same "header" (precondition, condition, postcondition, and chunksize for the `parallel for` directive) succeed to each other, the threads will be assigned the *same* iteration chunks
- By default, `chunksize` is equal to `OMP_NUM_THREADS`
- Very useful when iterations take roughly the same time to perform (*e.g.*, dense linear algebra routines)

Dynamic Scheduling

`schedule(dynamic,chunksize)` divides the iteration space according to `chunksize`, and creates an "abstract" queue of iteration chunks. If a thread is done processing its chunk, it dequeues the next one from the queue. By default, `chunksize` is 1.
Very useful if the time to process individual iterations varies.

Parallel Loops IV

Specifying the Schedule Mode

Guided Scheduling

`guided,chunksize` Same behavior as `dynamic`, but the chunksize is divided by two each time a threads dequeues a new chunk. The minimum size is one, and so is the default.
Very useful if the time to process individual iterations varies, *and* the amount of work has a "trail"

Parallel Loops

Specifying the Schedule Mode I

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```
#include <unistd.h>
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>
const double MAX = 100000.;

double sum(const int n) {
    const int id = omp_get_thread_num();
    double f  = 0.0;
    const int bound = id == 0 ? n*1001 : n;

    for (int i = 0; i < bound; ++i)
      f += i;

    return f;
}
```

Parallel Loops

Specifying the Schedule Mode II

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```
int main(void) {
  printf("MAX = %.2f\n",MAX);
  double acc = 0.0;
  int* sum_until = malloc(MAX*sizeof(int));
  if (!sum_until) perror("malloc"), exit( EXIT_FAILURE );
  for (int i = 0; i < (int)MAX; ++i)  sum_until[i] = rand () % 100;
  #pragma omp parallel default(none) \
              shared(sum_until) firstprivate(acc)
  {  /* Use the OMP_SCHEDULE environment variable on the command
      * line to specify the type of scheduling you want, e.g.:
      * export OMP_SCHEDULE="static" or OMP_SCHEDULE="dynamic,10"
      * or OMP_SCHEDULE="guided,100"; ./omp_schedule
      */
    #pragma omp for schedule(runtime)
    for (int i = 0; i < bound; i+=1) {
        acc += sum( sum_until[i] );
    }
    printf ("[%d]\tMy sum = %.2f\n", omp_get_thread_num(), acc);
  }
  free(sum_until);
  return 0;
}
```

Figure: omp_for_schedule.c

Parallel Loops

Specifying the Schedule Mode: Outputs I

```
szuckerm@evans201g:examples$ gcc -std=c99 -Wall -Wextra -pedantic \
                             -O3 -o omp_schedule omp_for_schedule.c
szuckerm@evans201g:examples$ export OMP_NUM_THREADS=4 OMP_PROC_BIND=true
```

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="static"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[0] My sum = 41299239778797.00
[1] My sum = 40564464.00
[3] My sum = 40174472.00
[2] My sum = 40502412.00

real    0m11.911s
user    0m11.930s
sys 0m0.004s
```

Parallel Loops

Specifying the Schedule Mode: Outputs I

```
szuckerm@evans201g:examples$ gcc -std=c99 -Wall -Wextra -pedantic \
                             -O3 -o omp_schedule omp_for_schedule.c
szuckerm@evans201g:examples$ export OMP_NUM_THREADS=4 OMP_PROC_BIND=true
```

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="static"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[0] My sum = 41299239778797.00
[1] My sum = 40564464.00
[3] My sum = 40174472.00
[2] My sum = 40502412.00

real    0m11.911s
user    0m11.930s
sys 0m0.004s
```

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="static,1"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[0] My sum = 41487115603934.00
[1] My sum = 40266669.00
[3] My sum = 40319644.00
[2] My sum = 40468898.00

real    0m11.312s
user    0m11.356s
sys 0m0.004s
```

Parallel Loops

Specifying the Schedule Mode: Outputs II

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="dynamic,1000"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[0] My sum = 1661647855868.00
[1] My sum = 55011312.00
[2] My sum = 46974801.00
[3] My sum = 58218664.00

real    0m0.546s
user    0m0.576s
sys 0m0.004s
```

Parallel Loops

Specifying the Schedule Mode: Outputs II

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="dynamic,1000"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[0] My sum = 1661647855868.00
[1] My sum = 55011312.00
[2] My sum = 46974801.00
[3] My sum = 58218664.00

real    0m0.546s
user    0m0.576s
sys 0m0.004s
```

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="dynamic,1"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[1] My sum = 57886783.00
[0] My sum = 76809786053.00
[2] My sum = 47423265.00
[3] My sum = 56452544.00

real    0m0.023s
user    0m0.059s
sys 0m0.004s
```

Parallel Loops

Specifying the Schedule Mode: Outputs III

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="guided,1000"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[0] My sum = 30922668944167.00
[3] My sum = 44855495.00
[2] My sum = 45989686.00
[1] My sum = 40596797.00

real    0m8.437s
user    0m8.452s
sys 0m0.008s
```

Parallel Loops

Specifying the Schedule Mode: Outputs III

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="guided,1000"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[0] My sum = 30922668944167.00
[3] My sum = 44855495.00
[2] My sum = 45989686.00
[1] My sum = 40596797.00

real    0m8.437s
user    0m8.452s
sys 0m0.008s
```

```
szuckerm@evans201g:examples$ export OMP_SCHEDULE="guided,1"
szuckerm@evans201g:examples$ time ./omp_schedule
MAX = 100000.00
[0] My sum = 17508269385607.00
[1] My sum = 49603788.00
[2] My sum = 40584346.00
[3] My sum = 54438904.00

real    0m5.401s
user    0m5.438s
sys 0m0.008s
```

Parallel Loops

The `lastprivate` Clause

```
int main(void) {
    double acc = 0.0; const int bound = MAX;
    printf("[%d]\tMAX = %.2f\n",omp_get_thread_num(),MAX);
    int* sum_until = smalloc(MAX*sizeof(int));
    for (int i = 0; i < bound; ++i)
        sum_until[i] = rand () % 100;
    #pragma omp parallel for default(none) shared(sum_until) \
                schedule(runtime) firstprivate(acc) lastprivate(acc)
    for (int i = 0; i < bound; i+=1)
        acc += sum( sum_until[i] );
    printf("Value of the last thread to write to acc = %.2f\n",acc);
    free(sum_until);
    return EXIT_SUCCESS;
}
```

Figure: omp_for_lastprivate.c

Incrementing a Global Counter I

Racy OpenMP Version

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```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>
unsigned long g_COUNTER = 0;

int
main(void)
{
  int n_threads = 1;
  #pragma omp parallel default(none) \
              shared(n_threads,stdout,g_COUNTER)
  {
    #pragma omp master
    {
      n_threads = omp_get_num_threads();
      printf("n_threads = %d\t",n_threads); fflush(stdout);
    }

    ++g_COUNTER;
  }
```

Incrementing a Global Counter II

Racy OpenMP Version

```
  printf("g_COUNTER = %lu\n",g_COUNTER);
  return EXIT_FAILURE;
}
```

```
szuckerm@evans201g:examples$ for i in $(seq 100)
> do ./global_counter ;done|sort|uniq
n_threads = 4   g_COUNTER = 2
n_threads = 4   g_COUNTER = 3
n_threads = 4   g_COUNTER = 4
```

Incrementing a Global Counter

Using a Critical Section

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```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>
unsigned long g_COUNTER = 0;

int main(void) {
  int n_threads = 1;
  #pragma omp parallel default(none) \
              shared(n_threads,stdout,g_COUNTER)
  {
    #pragma omp master
    {
      n_threads = omp_get_num_threads();
      printf("n_threads = %d\t",n_threads); fflush(stdout);
    }

    #pragma omp critical
    { ++g_COUNTER; }
  }
  printf("g_COUNTER = %lu\n",g_COUNTER);
  return EXIT_FAILURE;
}
```

Incrementing a Global Counter

Using an Atomic Section

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```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>
unsigned long g_COUNTER = 0;

int main(void) {
  int n_threads = 1;
  #pragma omp parallel default(none) \
              shared(n_threads,stdout,g_COUNTER)
  {
    #pragma omp master
    {
      n_threads = omp_get_num_threads();
      printf("n_threads = %d\t",n_threads); fflush(stdout);
    }

    #pragma omp atomic
    ++g_COUNTER;
  }
  printf("g_COUNTER = %lu\n",g_COUNTER);
  return EXIT_FAILURE;
}
```

Synchronization in OpenMP I

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`critical` Directive

`#pragma omp critical [(name)]`

Guarantees that only one thread can access the sequence of instructions contained in the (named) critical section. If no name is specified, an "anonymous" name is automatically generated.

`atomic` Directive

`#pragma omp atomic`

Guarantees the atomicity of the *single* arithmetic instruction that follows. On architectures that support atomic instructions, the compiler can generate a low-level instruction to ensure the atomicity of the operation. Otherwise, `atomic` is equivalent to `critical`.

Synchronization in OpenMP II

`barrier` Directive

```
#pragma omp barrier
```

All threads from a given parallel region must wait at the barrier. All `parallel` regions have an implicit barrier. All `omp for` loops do too. So do `single` regions.

`single` Directive

Guarantees that a single thread will execute the sequence of instructions located in the `single` region, and the region will be executed only once. There is an implicit barrier at the end of the region.

Synchronization in OpenMP III

`master` Directive

Guarantees that only the master thread (with $ID = 0$) will execute the sequence of instructions located in the `single` region, and the region will be executed only once. There is NO implicit barrier at the end of the region.

`nowait` Clause

`nowait` can be used on `omp for`, `single`, and `critical` directives to remove the implicit barrier they feature.

Tasking in OpenMP

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OpenMP 3.x brings a new way to express parallelism: tasks.

- Tasks must be created from within a `single` region
- A task is spawned by using the directive `#pragma omp task`
- Tasks synchronize with their siblings (*i.e.*, tasks spawned by the same parent task) using `#pragma omp taskwait`

Case Study: Fibonacci Sequence

We'll use the Fibonacci numbers example to illustrate the use of tasks:

```
/**
 * \brief Computes Fibonacci numbers
 * \param n the Fibonacci number to compute
 */
u64 xfib(u64 n) {
    return n < 2 ? // base case?
           n     : // fib(0) = 0, fib(1) = 1
           xfib(n-1) + xfib(n-2);
}
```

	Average Time (cycles)
Sequential - Recursive	196051726.08

Table: Fibonacci(37), 50 repetitions, on Intel i7-2640M CPU @ 2.80GHz

Computing Fibonacci Numbers: Headers I

utils.h, common.h, and mt.h

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```
#ifndef UTILS_H_GUARD
#define UTILS_H_GUARD
#include <stdio.h>
#include <stdlib.h>
#include <errno.h>
#include <stdint.h>
#include "rdtsc.h"

static inline void fatal(const char* msg) {
    perror(msg), exit(errno);
}
static inline void sfree(void* p) {
    if (p) { *(char*)p = 0;}  free(p);
}
static inline void* scalloc(size_t nmemb, size_t size) {
  void* p = calloc(nmemb,size);
  if (!p) { fatal("calloc"); }
  return p;
}
static inline void* smalloc(size_t size) {
```

Computing Fibonacci Numbers: Headers II

utils.h, common.h, and mt.h

```
  void* p = malloc(size);
  if (!p) { fatal("malloc"); }
  return p;
}
static inline void usage(const char* progname) {
  printf("USAGE: %s positive_number\n", progname);
  exit(0);
}
void u64_measure(u64 (*func)(u64),  u64 n,
                 u64 n_reps, const char* msg);
void u64func_time(u64 (*func)(u64), u64 n,
                  const char* msg);
#endif // UTILS_H_GUARD
```

Computing Fibonacci Numbers: Headers III

utils.h, common.h, and mt.h

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```
#ifndef COMMON_H_GUARD
#define COMMON_H_GUARD
#include "utils.h" // for smalloc(), sfree(), fatal(), scalloc(), ...
#define FIB_THRESHOLD 20

typedef uint64_t u64; typedef uint32_t u32; typedef uint16_t u16;
typedef uint8_t  u8;  typedef  int64_t s64; typedef  int32_t s32;
typedef  int16_t s16; typedef  int8_t  s8;

u64   xfib(u64);     u64   trfib(u64,u64,u64);
u64   trFib(u64);    u64   sfib(u64);
u64   memoFib(u64);  u64   memofib(u64,u64*);

void* mt_memofib(void*); u64   mt_memoFib(u64);
void* mtfib(void*);      u64   mtFib(u64);

u64   oFib(u64);       u64   ofib(u64);
u64   o_memoFib(u64);  u64   o_memofib(u64,u64*);
```

Computing Fibonacci Numbers: Headers IV

utils.h, common.h, and mt.h

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```
#endif /* COMMON_H_GUARD */
```

```
#ifndef MT_H_GUARD
#define MT_H_GUARD
#include <pthread.h>
typedef struct fib_s     { u64 *up,          n; }     fib_t;
typedef struct memofib_s { u64 *up, *vals, n; } memofib_t;
static inline pthread_t* spawn(void* (*func)(void*), void* data) {
    pthread_t* thread = smalloc(sizeof(pthread_t)); int error = 0;
    do {
      errno = error = pthread_create(thread,NULL,func,data);
    } while (error == EAGAIN);
    if (error) fatal("pthread_create");
    return thread;
}
static inline void sync(pthread_t* thread) {
    int error = 0; void* retval = NULL;
    if ( (errno = ( error = pthread_join(*thread, &retval) ) ) )
        fatal("pthread_join");
```

Computing Fibonacci Numbers: Headers V

utils.h, common.h, and mt.h

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```
    sfree(thread);
}
#endif // MT_H_GUARD
```

Computing Fibonacci Numbers: Code I

Naïve Pthread and OpenMP

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```
#include "common.h"
#include "mt.h"
void* mtfib(void* frame) {
    fib_t* f = (fib_t*) frame;
    u64 n  = f->n, *up = f->up;
    if (n < FIB_THRESHOLD)
        *up = sfib(n), pthread_exit(NULL);
    u64 n1 = 0, n2 = 0;
    fib_t frame1 = { .up = &n1, .n = f->n-1 },
          frame2 = { .up = &n2, .n = f->n-2 };
    pthread_t *thd1 = spawn(mtfib,&frame1),
              *thd2 = spawn(mtfib,&frame2);
    sync(thd1); sync(thd2);
    *up = n1+n2;
    return NULL;
}
u64  mtFib(u64 n) {
    u64 result = 0; fib_t f = { .up = &result, .n = n };
    (void)mtfib(&f);
    return result;
}
```

Computing Fibonacci Numbers: Code II

Naïve Pthread and OpenMP

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```
#include "common.h"
#include <omp.h>

u64 ofib(u64 n) { u64 n1, n2;
    if (n < FIB_THRESHOLD)  return sfib(n);
#   pragma omp task shared(n1)
    n1 = ofib(n-1);
#   pragma omp task shared(n2)
    n2 = ofib(n-2);
#   pragma omp taskwait
    return n1 + n2;
}

u64 oFib(u64 n) { u64 result = 0;
#   pragma omp parallel
    {
#       pragma omp single nowait
        { result = ofib(n); }
    } // parallel
    return result;
}
```

Computing Fibonacci Numbers: Code III

Naïve Pthread and OpenMP

	Average Time (cycles)
Sequential - Recursive	196051726.08
Parallel - PThread	2837871164.24
Parallel - OpenMP	17707012.14

Table: Fibonacci(37), 50 repetitions, on Intel i7-2640M CPU @ 2.80GHz

Computing Fibonacci Numbers: Code I

Memoization using Serial, Pthread and OpenMP

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```
#include "common.h"
#include "mt.h"
void* mt_memofib(void* frame) { memofib_t* f = (memofib_t*) frame;
  u64 n = f->n *vals = f->vals, *up = f->up;
  if (n < FIB_THRESHOLD)  *up = vals[n] = sfib(n), pthread_exit(NULL)
  if (vals[n] == 0) { u64 n1 = 0, n2 = 0;
    memofib_t frame1 = {.up=&n1,.n=f->n-1,.vals=vals},
              frame2 = {.up=&n2,.n=f->n-2,.vals=vals};
    pthread_t *thd1  = spawn(mt_memofib,&frame1),
              *thd2  = spawn(mt_memofib,&frame2);
    sync(thd1); sync(thd2);
    vals[n] = n1 + n2; }
  *up = vals[n], pthread_exit(NULL);
}
u64 mt_memoFib(u64 n) { u64 result = 0;
    u64* fibvals = scalloc(n+1,sizeof(u64));
    fibvals[1]=1; memofib_t f={.up=&result,.n=n,.vals=fibvals};
    (void)mt_memofib(&f);
    return result;
}
```

Computing Fibonacci Numbers: Code II

Memoization using Serial, Pthread and OpenMP

```
#include "common.h"
#include <omp.h>
u64 o_memofib(u64 n, u64* vals) {
  if (n < FIB_THRESHOLD) return sfib(n);
  if (vals[n] == 0) { u64 n1 = 0, n2 = 1;
#   pragma omp task shared(n1,vals)
    n1 = o_memofib(n-1,vals);
#   pragma omp task shared(n2,vals)
    n2 = o_memofib(n-2,vals);
#   pragma omp taskwait
    vals[n] = n1 + n2;
  }
  return vals[n];
}
u64 o_memoFib(u64 n) {
  u64 result=0, *fibvals=calloc(n+1,sizeof(u64));
# pragma omp parallel
  {
#   pragma omp single nowait
    { fibvals[1] = 1; result = o_memofib(n,fibvals); }
  }
  return result; }
```

Computing Fibonacci Numbers: Code III

Memoization using Serial, Pthread and OpenMP

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```
#include "common.h"

u64 memofib(u64 n, u64* vals) {
    if (n < 2)
        return n;
    if (vals[n] == 0)
        vals[n] = memofib(n-1,vals) + memofib(n-2,vals);
    return vals[n];
}

u64  memoFib(u64 n) {
    u64* fibvals = calloc(n+1,sizeof(u64));
    fibvals[0] = 0; fibvals[1] = 1;
    u64 result = memofib(n,fibvals);
    sfree(fibvals);
    return result;
}
```

Computing Fibonacci Numbers: Code IV

Memoization using Serial, Pthread and OpenMP

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	Average Time (cycles)
Sequential - Recursive	196051726.08
Parallel - PThread	2837871164.24
Parallel - OpenMP	17707012.14
Parallel - PThread - Memoization	2031161888.56
Parallel - OpenMP - Memoization	85899.58
Sequential - Memoization	789.70

Table: Fibonacci(37), 50 repetitions, on Intel i7-2640M CPU @ 2.80GHz

Computing Fibonacci Numbers: Code I

When Serial is MUCH Faster Than Parallel

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```
#include "common.h"
u64 trfib(u64 n, u64 acc1, u64 acc2) {
    return n < 2 ?
           acc2  :
           trfib( n-1, acc2, acc1+acc2);
}
u64 trFib(u64 n) {  return trfib(n, 0, 1);  }
```

```
#include "common.h"
u64  sfib(u64 n) {
    u64 n1 = 0, n2 = 1, r = 1;
    for (u64 i = 2; i < n; ++i) {
        n1 = n2;
        n2 = r;
        r  = n1 + n2;
    }
    return r;
}
```

Computing Fibonacci Numbers: Code II

When Serial is MUCH Faster Than Parallel

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	Average Time (cycles)
Sequential - Recursive	196051726.08
Parallel - PThread	2837871164.24
Parallel - OpenMP	17707012.14
Parallel - PThread - Memoization	2031161888.56
Parallel - OpenMP - Memoization	85899.58
Sequential - Memoization	789.70
Sequential - Tail Recursive	110.78
Sequential - Iterative	115.02

Table: Fibonacci(37), 50 repetitions, on Intel i7-2640M CPU @ 2.80GHz

Learning More About Multi-Threading and OpenMP

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Books (from most theoretical to most practical)

- Herlihy and Shavit 2008
- Rünger and Rauber 2013
- Kumar 2002
- Chapman, Jost, and Pas 2007

Internet Resources

- "The OpenMP® API specification for parallel programming" at `openmp.org`
  - Provides all the specifications for OpenMP, in particular OpenMP 3.1 and 4.0
  - Lots of tutorials (see `http://openmp.org/wp/resources/#Tutorials`)
- The Wikipedia article at `http://en.wikipedia.org/wiki/OpenMP`

Food for Thoughts

- Sutter 2005 (available at `http://www.gotw.ca/publications/concurrency-ddj.htm`)
- Lee 2006 (available at `http://www.eecs.berkeley.edu/Pubs/TechRpts/2006/EECS-2006-1.pdf`)
- Boehm 2005 (available at `http://www.hpl.hp.com/techreports/2004/HPL-2004-209.pdf`)

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