An Introduction to Parallel Programming:

A hands-on Introduction (using OpenMP)

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Human Learning Group
(retired from Intel Aug'2023)

With a lot of help from Helen He, Alice Koniges, David Eder, and many more

Introduction

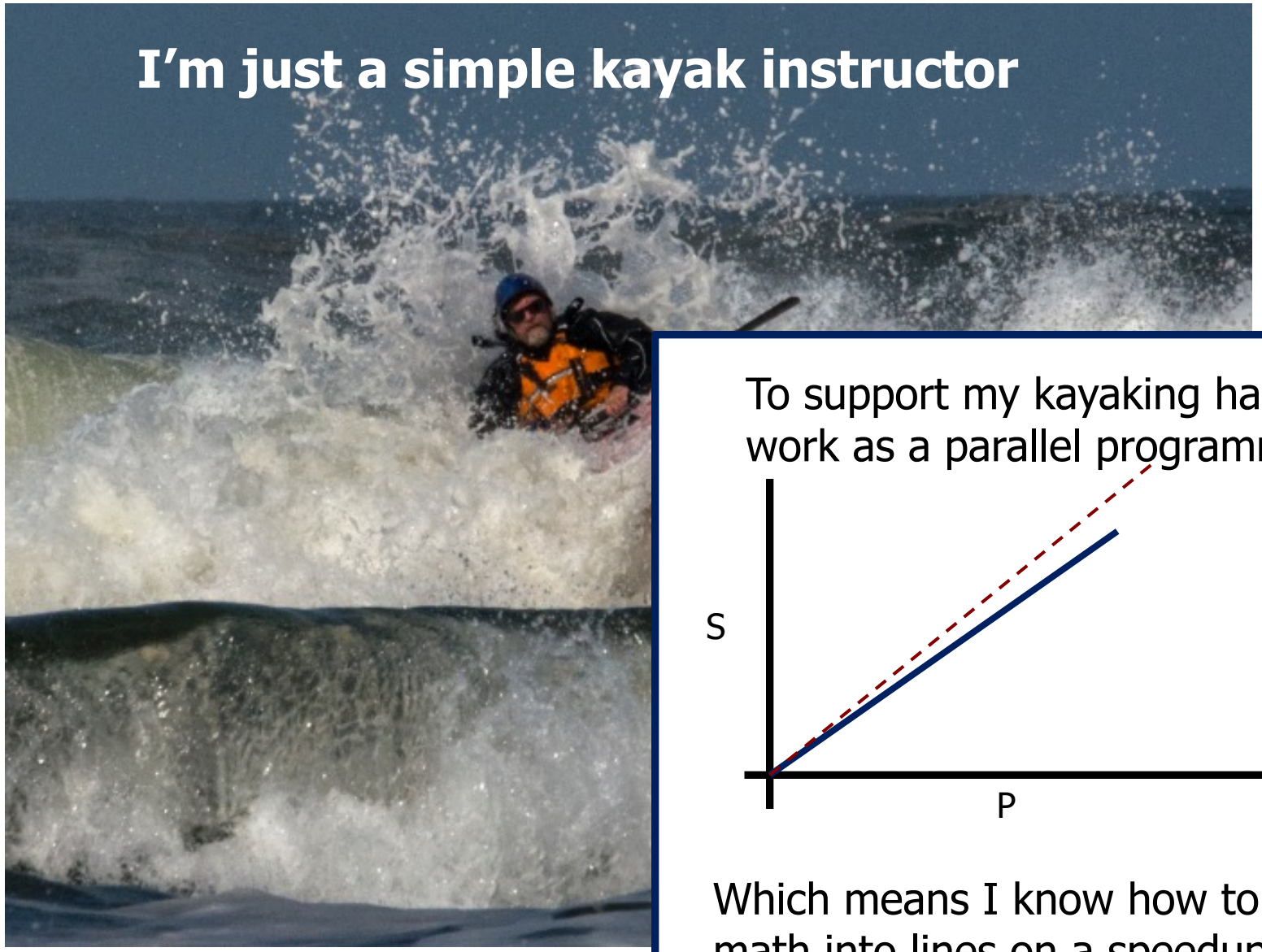


Photo © by Greg Clopton, 2014

To support my kayaking habit, I work as a parallel programmer

Which means I know how to turn math into lines on a speedup plot

Preliminaries: Part 1

- Our plan for the day .. Active learning!
  - We will mix short lectures with short exercises.

- Please follow these simple rules
  - Do the exercises that we assign and then change things around and experiment.
    - Embrace active learning!
  - Don't cheat: Do Not look at the solutions before you complete an exercise … even if you get really frustrated.

Use homebrew to install gnu compilers on your Apple laptop

I tested this on a new (July 2023) MacBook Air with an Apple M2 CPU

Warning: Xcode uses the name gcc for Apple's clang compiler. Use Homebrew to load a real, gcc compiler.

- Download Xcode. Be sure to choose the command line tools option.
- Go to the homebrew web site (brew.sh). Cut and paste the command near the top of the page to install homebrew (in /opt/homebrew):

```
/bin/bash -c "$(curl -fsSL https://raw.githubusercontent.com/Homebrew/install/HEAD/install.sh)"
```

- Add /opt/homebrew/bin to your path. I did this by adding the following line to .zshrc

```
% export PATH=/opt/homebrew/bin:$PATH
```

- Install the latest gcc compiler

```
% brew install gcc
```

- This will install the compiler in /opt/homebrew/bin. Check /opt/homebrew/bin to see which gcc compiler was installed. In my case, it installed gcc-13
- Test the compiler (and the openmp option) with a simple hello world program

```
% gcc-13 –fopenmp hello.c
```

OpenMP Compilers on Apple Laptops: MacPorts

I have not tested this in a long time.
I greatly prefer homebrew.

But if you prefer MacPorts, this procedure should work.

- To use OpenMP on your Apple laptop:
- Download Xcode. Be sure to choose the command line tools option.
- Download and use MacPorts to install the latest gnu compilers.

```
sudo port selfupdate
```

Update to latest version of MacPorts

```
sudo port install gcc13
```

Grab version 13 gnu compilers (5-10 mins)

```
port select --list gcc
```

List versions of gcc on your system

```
sudo port select --set gcc mp-gcc13
```

Select the mp enabled version of the most recent gcc release

```
gcc -fopenmp hello.c
```

Test the installation with a simple program

The best way to master parallel computing …

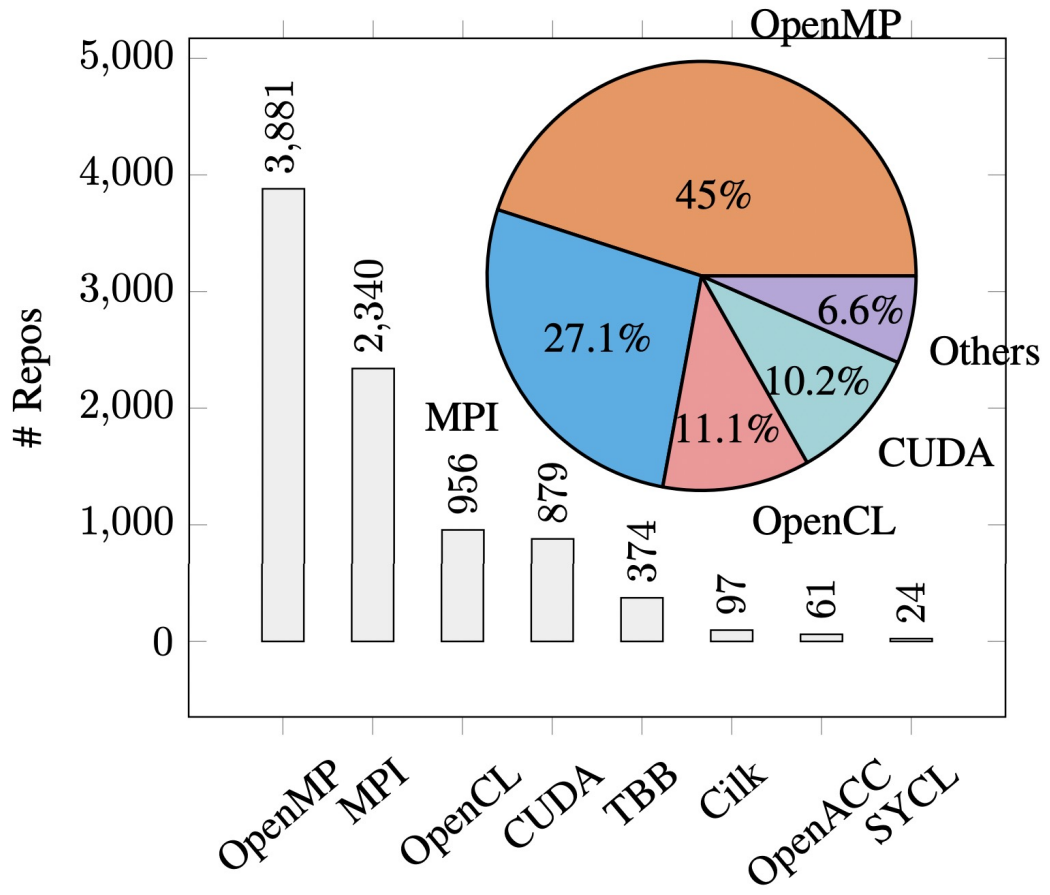
start with a simple approach to parallelism and build an intellectual foundation by writing parallel code.

… and the simplest API for parallelism is?

Outline

- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- Memory Model
- OpenMP stuff we didn't cover
- Recap

OpenMP



In a dataset (HPCorpus) of all C/C++/Fortan github repositories from 2013-2023, OpenMP was found to be the most popular parallel programming model

Aggregate numbers over all repositories from 2013 to 2023

Quantifying OpenMP: Statistical insights into usage and adoption,
Tal Kadosh, et al., HPEC'2023, https://arxiv.org/abs/2308.08002

Note: since we did not collect files with .cu or .cuf suffices, we undercounted CUDA usage in HPCorpus.

OpenMP* Overview

```
C$OMP FLUSH
#pragma omp critical
#pragma omp single
C$OMP THREADPRIVATE(/ABC/)
C$OMP ATOMIC
CALL OMP_SET_NUM_THREADS(10)
```

OpenMP: An API for Writing Parallel Applications

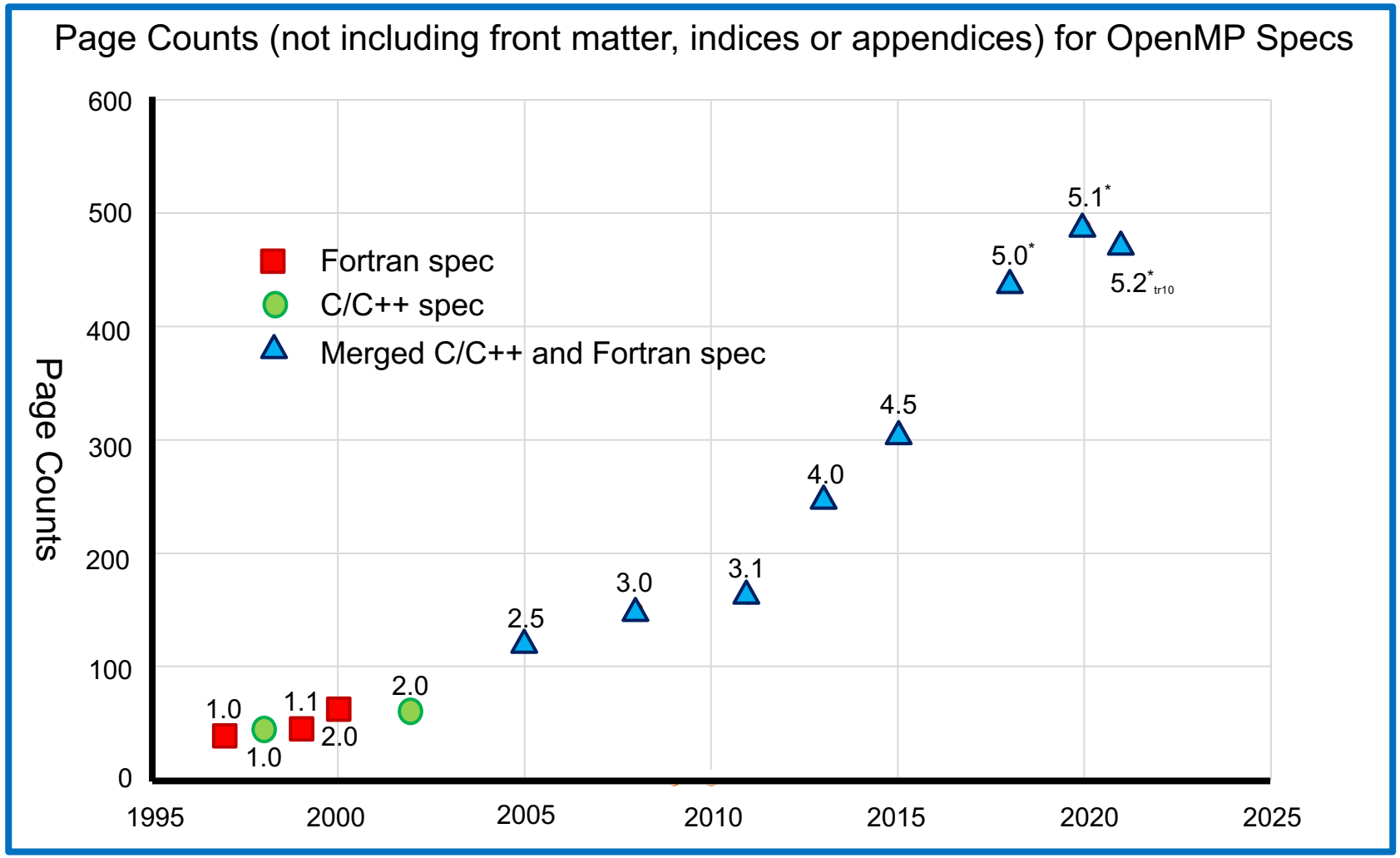
- A set of compiler directives and library routines for parallel application programmers
- Originally … Greatly simplifies writing multithreaded programs in Fortran, C and C++
- Later versions … supports non-uniform memories, vectorization and GPU programming

```
#pragma omp parallel for private(A, B)
C$OMP PARALLEL  REDUCTION (+: A, B)
C$OMP PARALLEL COPYIN(/blk/)
C$OMP DO lastprivate(XX)
#pragma omp atomic seq_cst
Nthrds = OMP_GET_NUM_PROCS()
omp_set_lock(lck)
```

* The name "OpenMP" is the property of the OpenMP Architecture Review Board.

The Growth of Complexity in OpenMP

Our goal in 1997 … A simple interface for application programmers

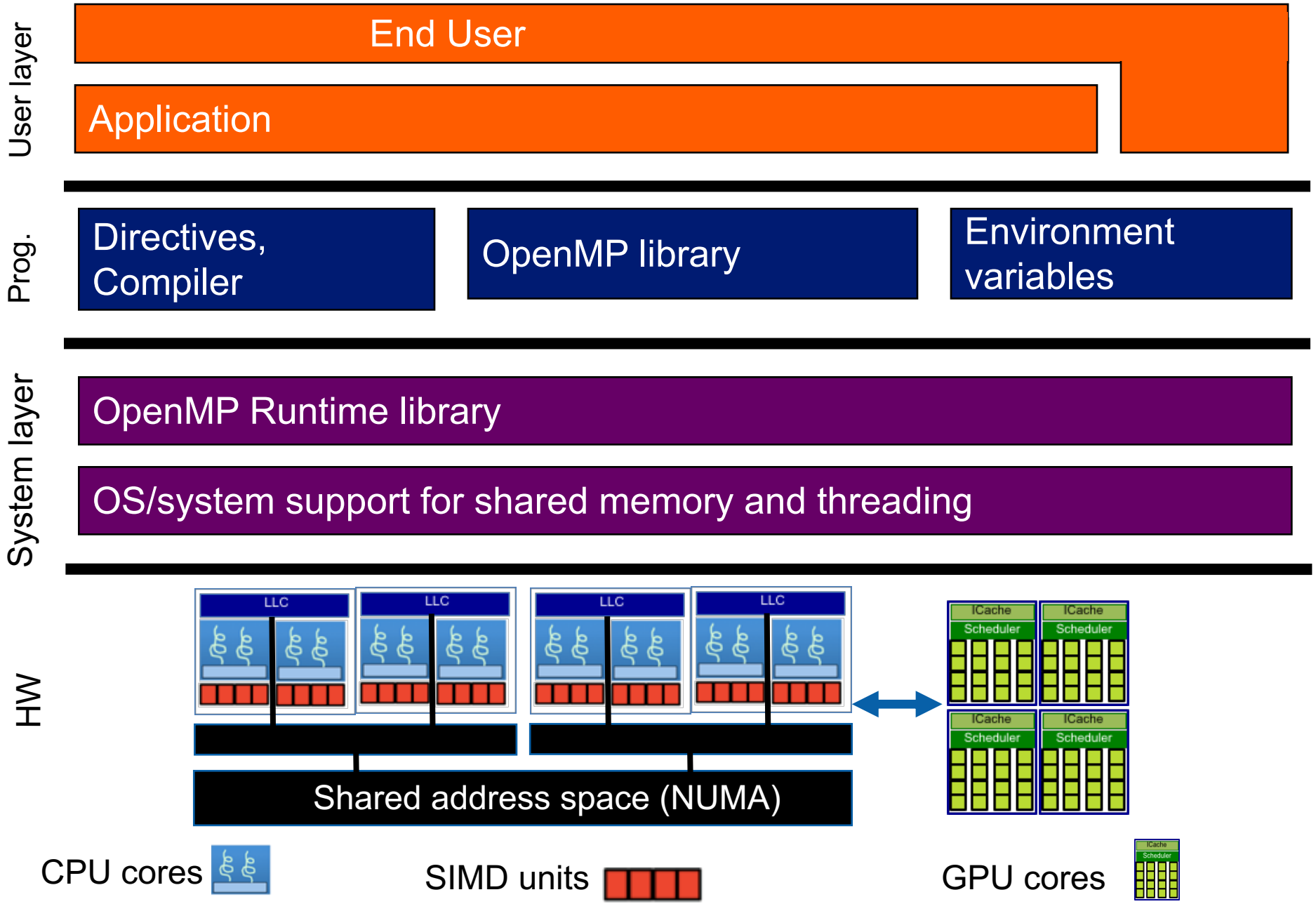


The full spec is overwhelming. We focus on the Common Core: the 21 items most people restrict themselves to

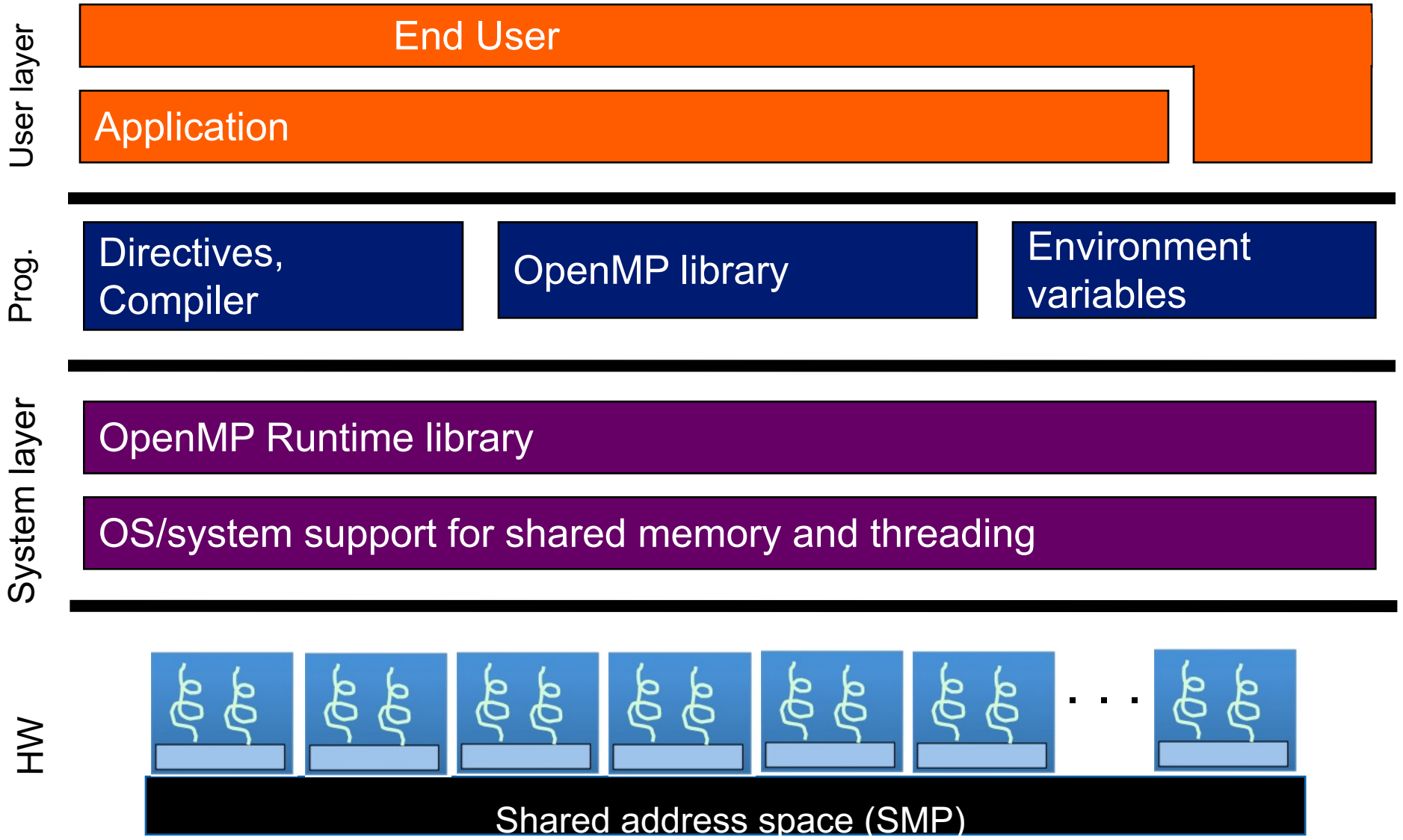
The OpenMP Common Core: Most OpenMP programs only use these 21 items

OpenMP pragma, function, or clause	Concepts
#pragma omp parallel	Parallel region, teams of threads, structured block, interleaved execution across threads.
void omp_set_thread_num() int omp_get_thread_num() int omp_get_num_threads()	Default number of threads and internal control variables. SPMD pattern: Create threads with a parallel region and split up the work using the number of threads and the thread ID.
double omp_get_wtime()	Speedup and Amdahl's law. False sharing and other performance issues.
setenv OMP_NUM_THREADS N	Setting the internal control variable for the default number of threads with an environment variable
#pragma omp barrier #pragma omp critical	Synchronization and race conditions. Revisit interleaved execution.
#pragma omp for #pragma omp parallel for	Worksharing, parallel loops, loop carried dependencies.
reduction(op:list)	Reductions of values across a team of threads.
schedule (static [,chunk]) schedule(dynamic [,chunk])	Loop schedules, loop overheads, and load balance.
shared(list), private(list), firstprivate(list)	Data environment.
default(none)	Force explicit definition of each variable's storage attribute
nowait	Disabling implied barriers on workshare constructs, the high cost of barriers, and the flush concept (but not the flush directive).
#pragma omp single	Workshare with a single thread.
#pragma omp task #pragma omp taskwait	Tasks including the data environment for tasks.

OpenMP Basic Definitions: Basic Solution Stack



OpenMP Basic Definitions: Basic Solution Stack



For the OpenMP Common Core, we focus on Symmetric Multiprocessor Case ….
i.e., lots of threads with “equal cost access” to memory

OpenMP Basic Syntax

- Most of OpenMP happens through compiler directives.

C and C++	Fortran
Compiler directives	
#pragma omp construct [clause [clause]…]	***!$OMP construct [clause [clause] …]***
Example	
#pragma omp parallel private(x) ***{*** ***}***	***!$OMP PARALLEL PRIVATE(X)*** ***!$OMP END PARALLEL***
Function prototypes and types:	
#include <omp.h>	***use OMP_LIB***

- Most OpenMP constructs apply to a “structured block”.
  - **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.
  - It’s OK to have an exit() within the structured block.

Exercise, Part A: Hello World

Verify that your environment works

- Write a program that prints “hello world”.

```
#include <stdio.h>
int main()
{




    printf(“ hello ”);
    printf(“ world \n”);

}
```

Exercise, Part B: Hello World

Verify that your OpenMP environment works

- Write a multithreaded program that prints “hello world”.

```
#include <omp.h>
#include <stdio.h>
int main()
{
 #pragma omp parallel
 {


    printf(“ hello ”);
    printf(“ world \n”);
 }
}
```

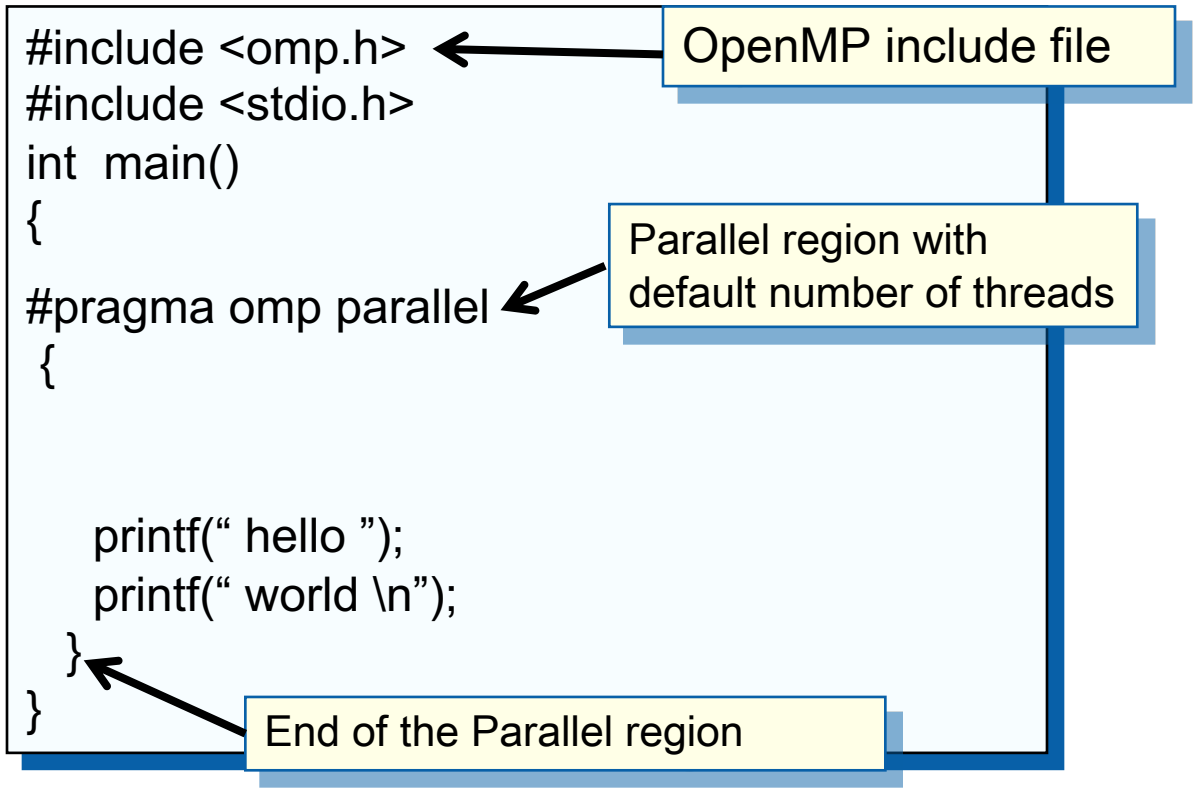
Switches for compiling and linking

gcc -fopenmp	**Gnu (Linux, OSX)**
cc –fopenmp	
icc -fopenmp	**Intel (Linux, OSX)**

Solution

A Multi-Threaded “Hello World” Program

- Write a multithreaded program where each thread prints “hello world”.



Sample Output:

hello hello world

world

hello hello world

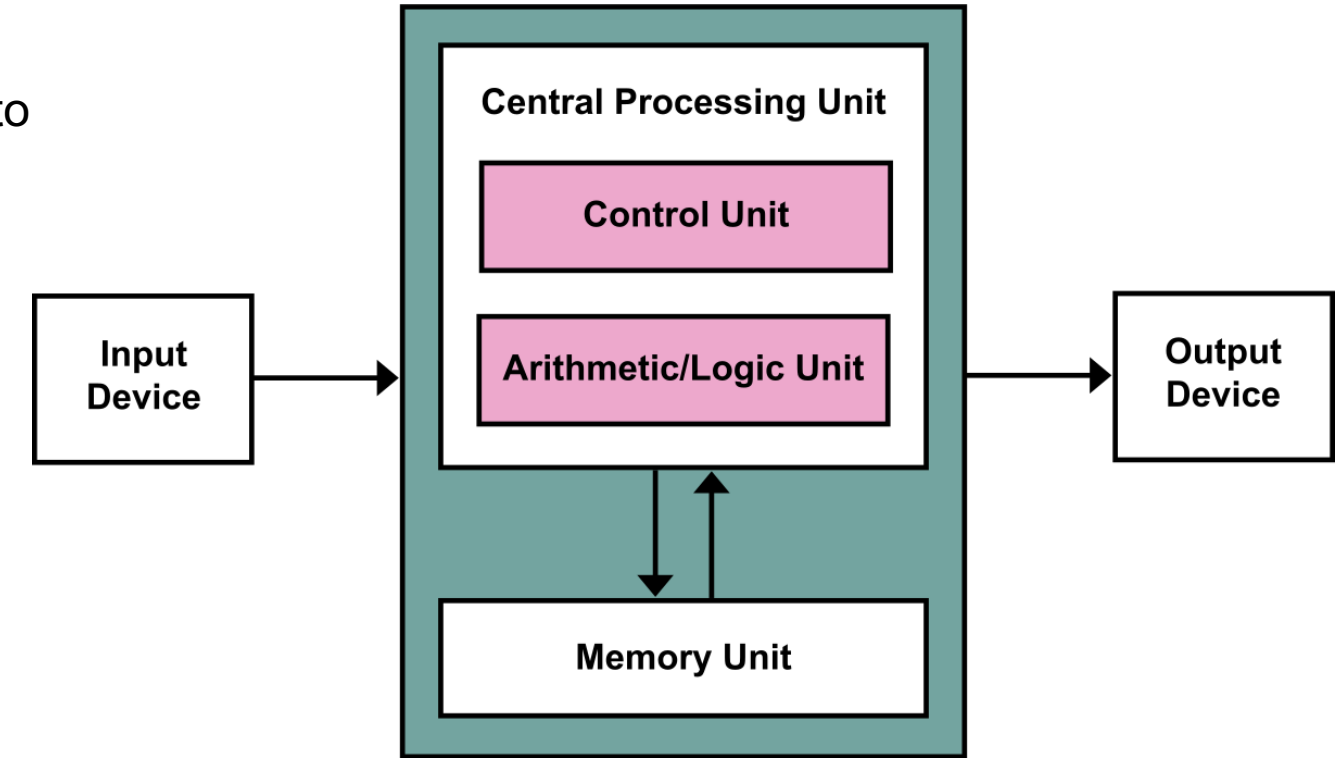
world

The statements are interleaved based on how the operating schedules the threads

A brief digression on the terminology of parallel computing

Let's agree on a few definitions:

- **Computer:**
  - A machine that transforms *input values* into *output values*.
  - Typically, a computer consists of Control, Arithmetic/Logic, and Memory units.
  - The transformation is defined by a stored **program** (von Neumann architecture).



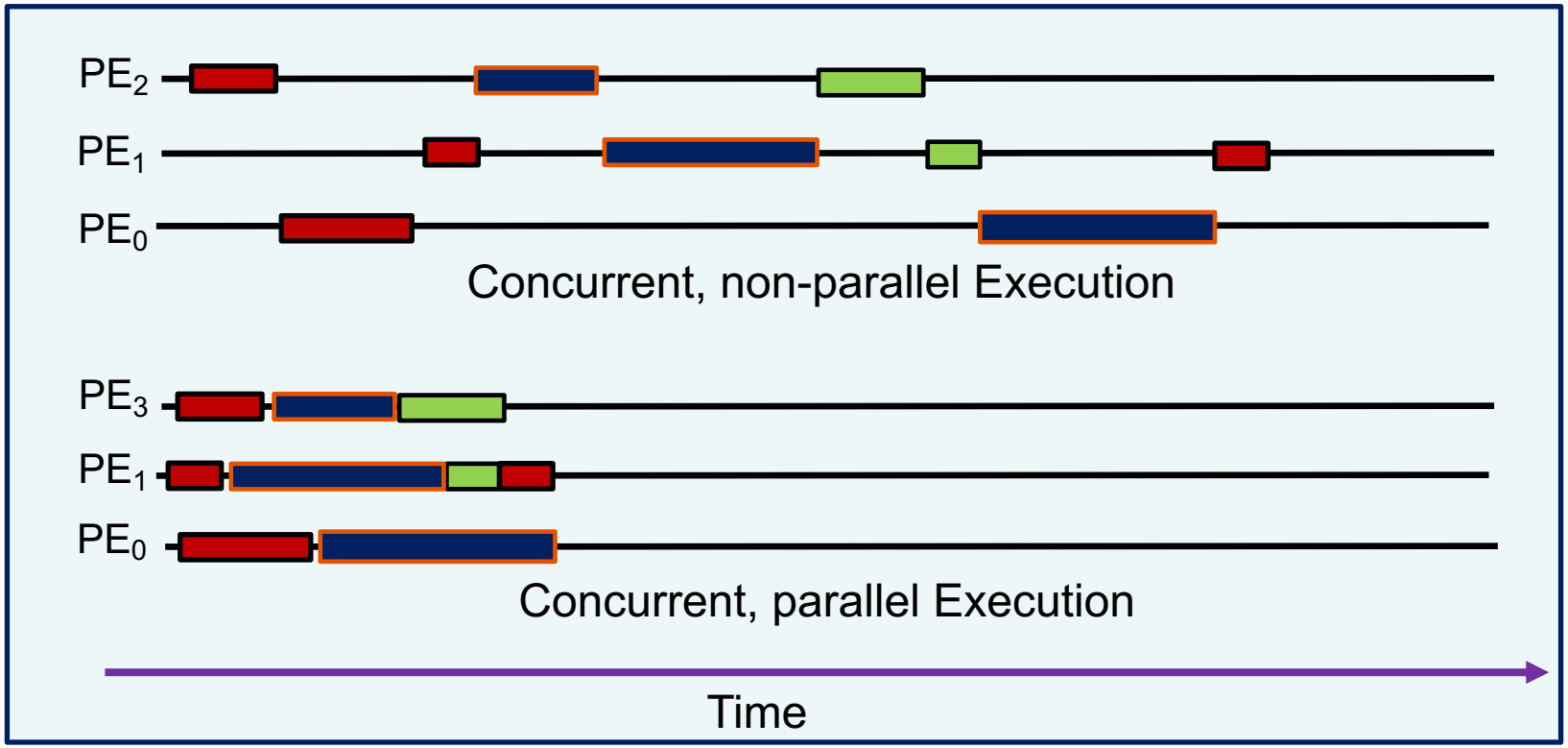
- **Task:**
  - A sequence of instructions plus a data environment. A program is composed of one or more tasks.

- **Active task:**
  - A task that is available to be scheduled for execution. When the task is moving through its sequence of instructions, we say it is making **forward progress**

- **Fair scheduling:**
  - When a scheduler gives each active task an equal *opportunity* for execution.

Concurrency vs. Parallelism

- Two important definitions:
  - Concurrency: A condition of a system in which multiple tasks are active and unordered. If **scheduled fairly**, they can be described as ***logically*** making **forward progress** at the same time.
  - Parallelism: A condition of a system in which multiple tasks are **actually** making **forward progress** at the same time.



PE = Processing Element

Figure from "An Introduction to Concurrency in Programming Languages" by J. Sottile, Timothy G. Mattson, and Craig E Rasmussen, 2010

Concurrency vs. Parallelism

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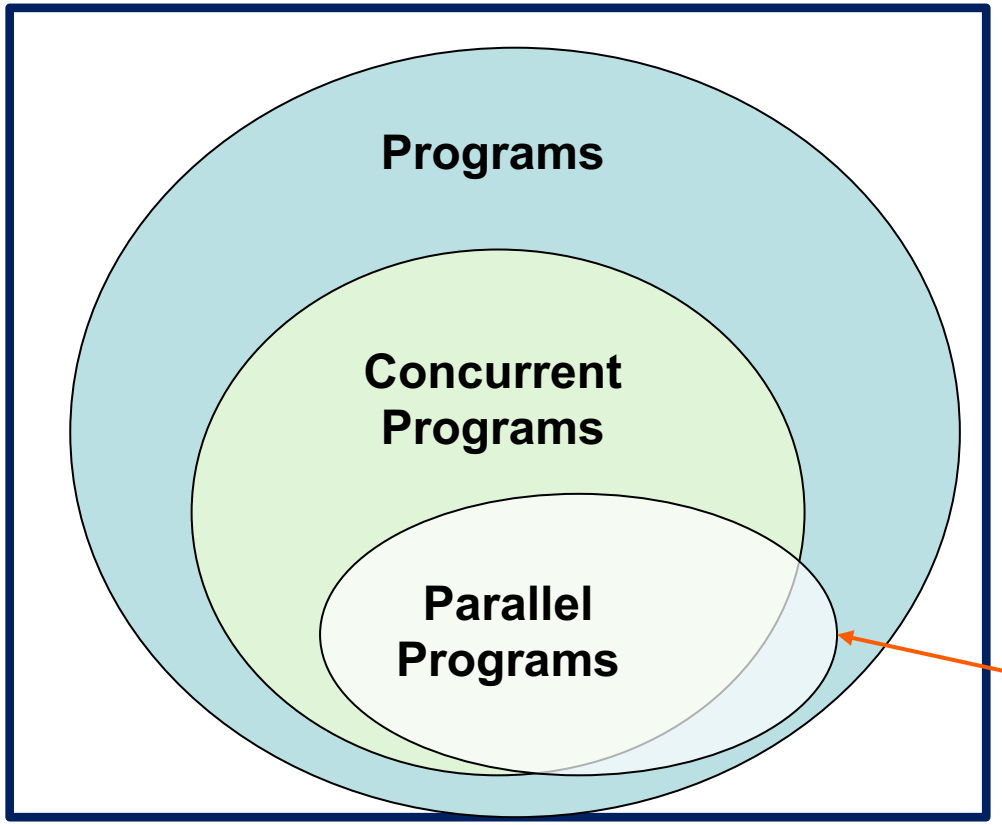


In most cases, parallel programs exploit concurrency in a problem to run tasks on multiple processing elements

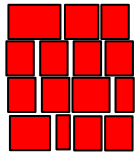
We use Parallelism to:
- Do more work in less time
- Work with larger problems

If tasks execute in "lock step" they are not concurrent, but they are still parallel. Example … a SIMD unit.

Figure from "An Introduction to Concurrency in Programming Languages" by J. Sottile, Timothy G. Mattson, and Craig E Rasmussen, 2010

Executing a program on CPUs and GPUs

Work decomposed into blocks



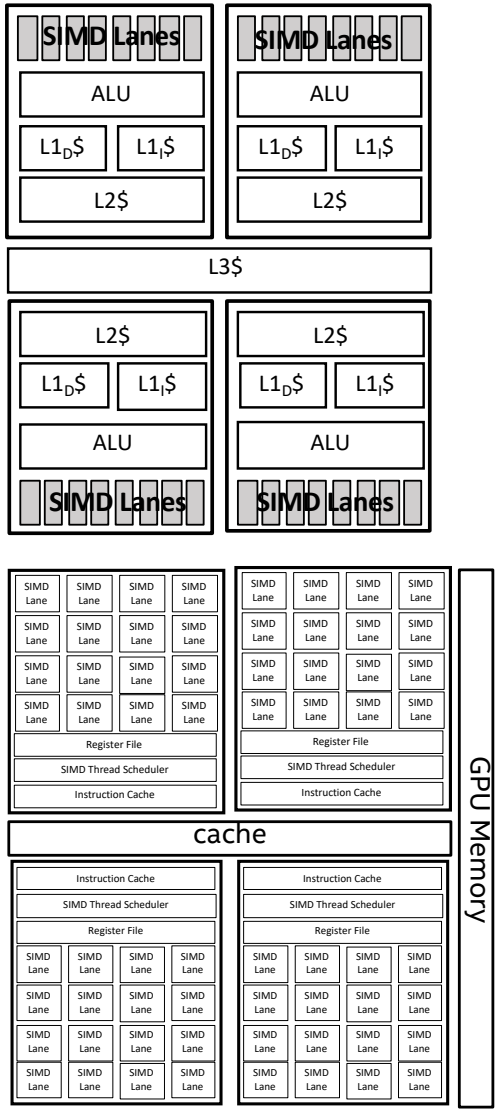
For a CPU

For a GPU

Program defines work

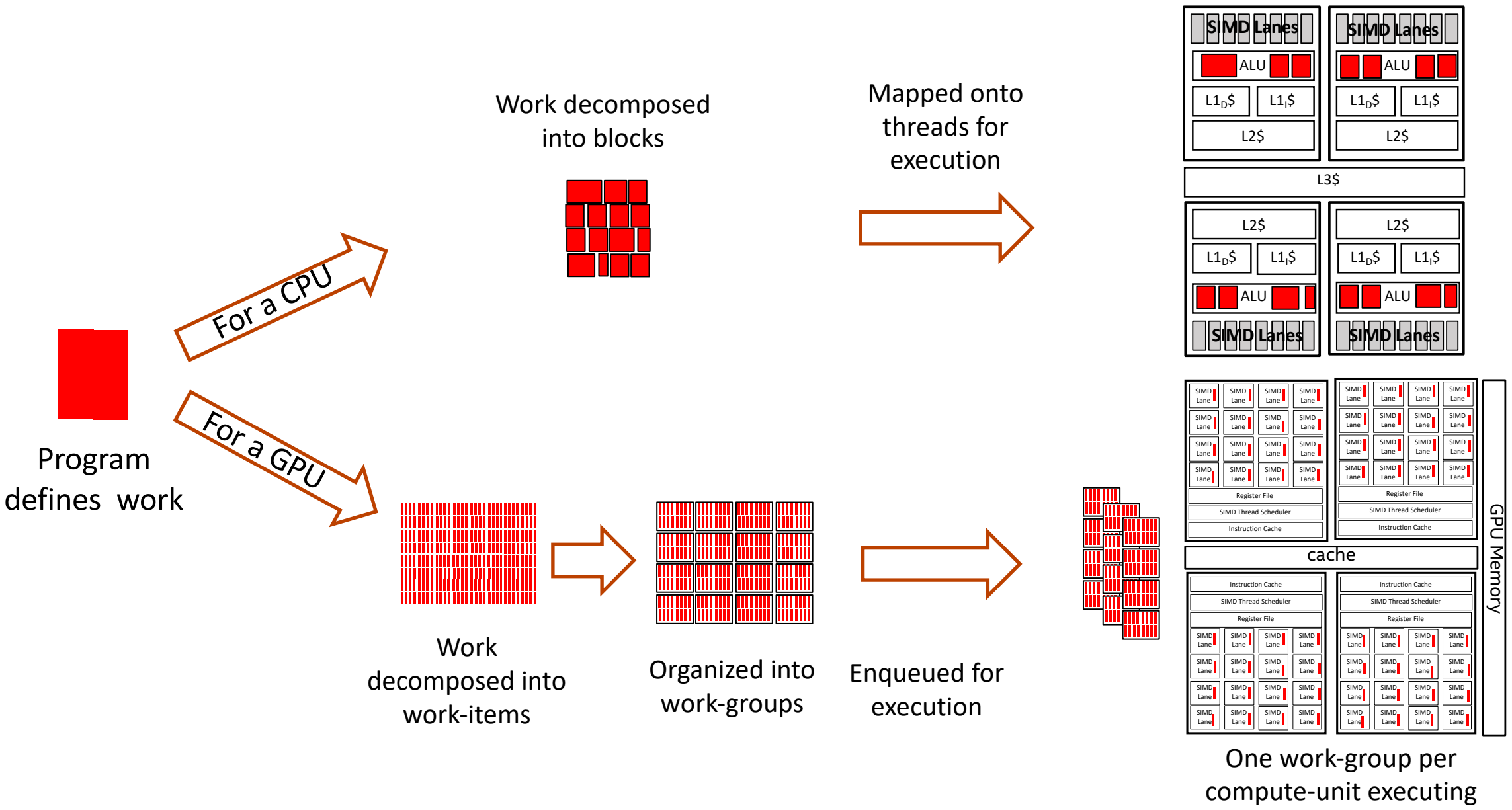
Work decomposed into work-items

Organized into work-groups

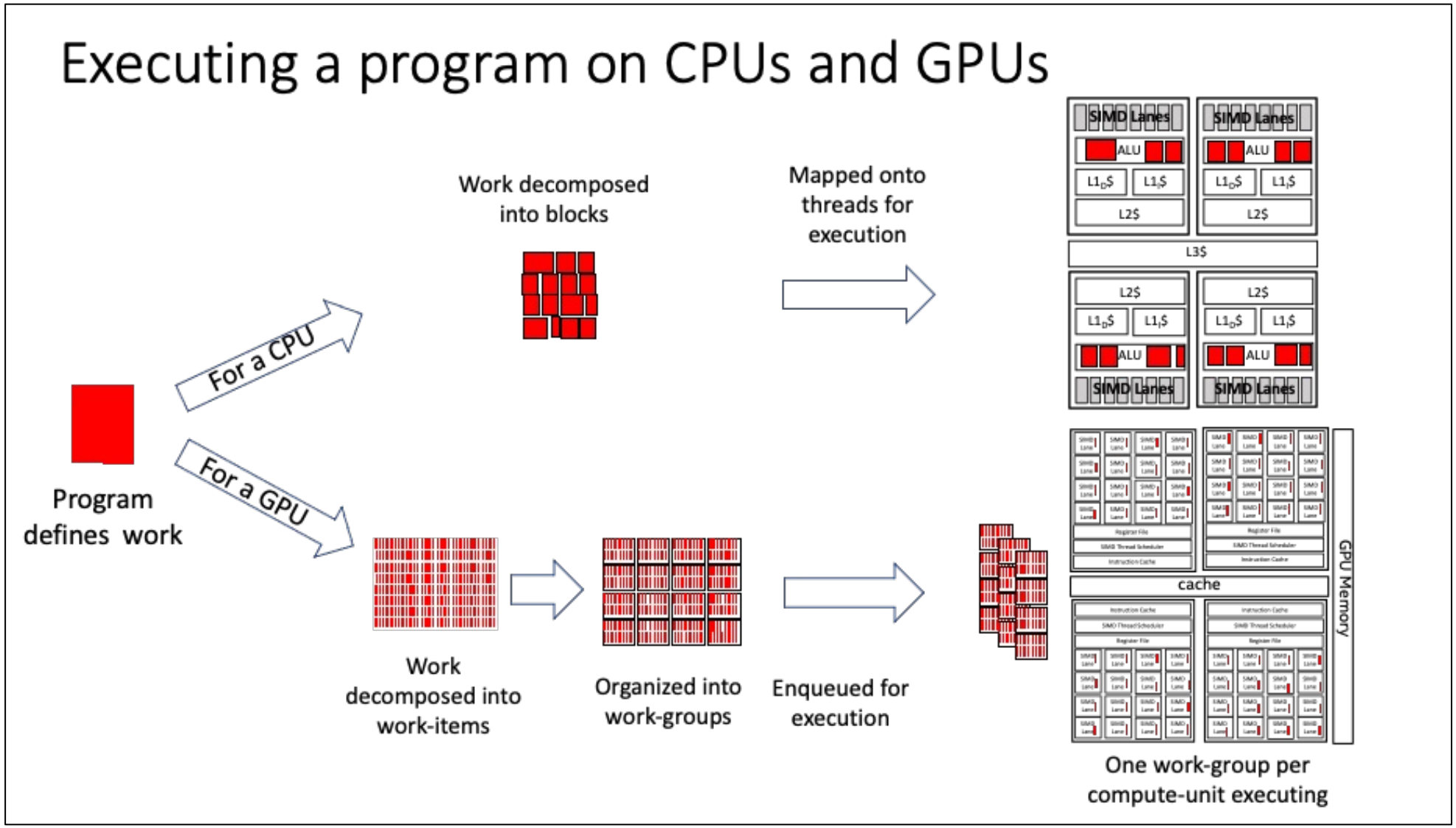


One work-group per compute-unit executing

Executing a program on CPUs and GPUs



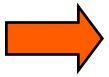
CPU/GPU execution modesl



For a CPU, the threads are all active and able to make forward progress.

For a GPU, any given work-group might be in the queue waiting to execute.

Outline



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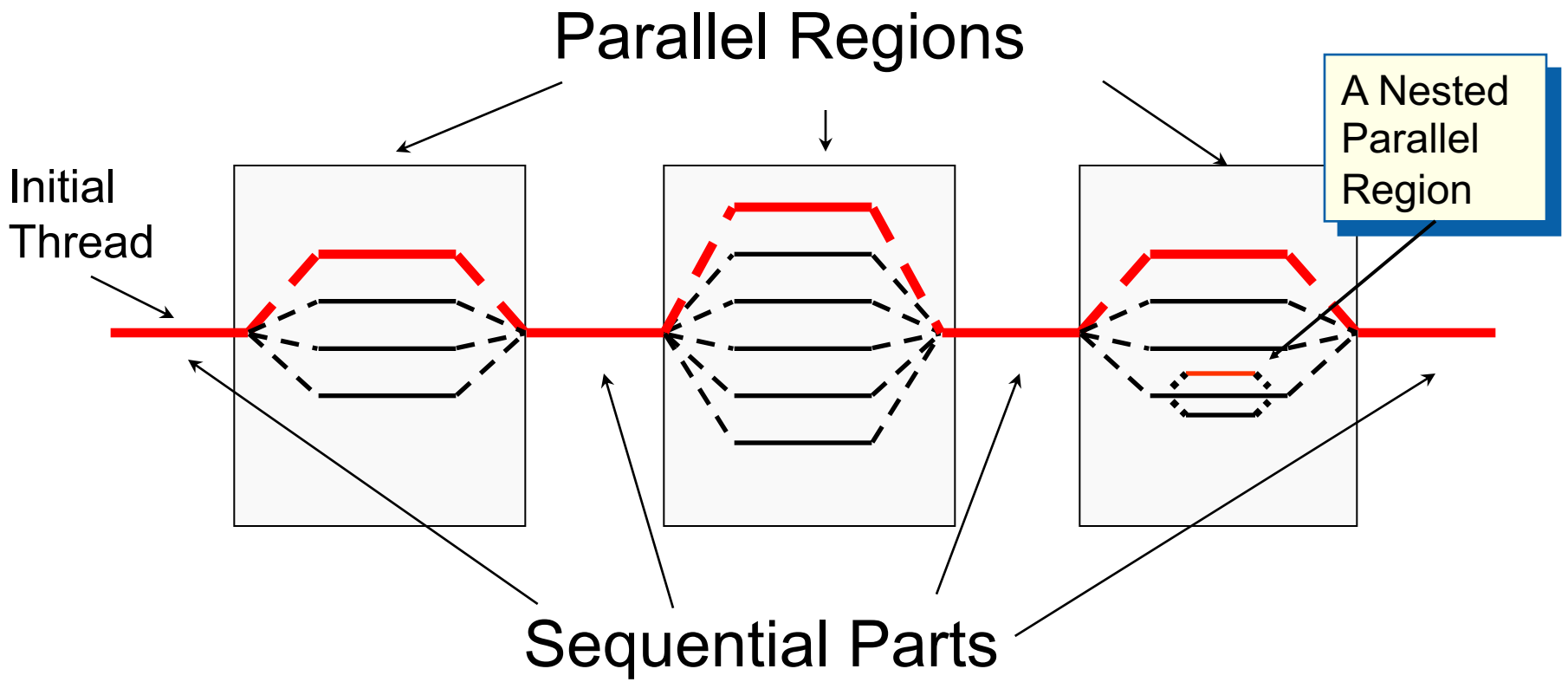
OpenMP Execution model:

The fork-Join model is also used with POSIX threads and std::thread in C++

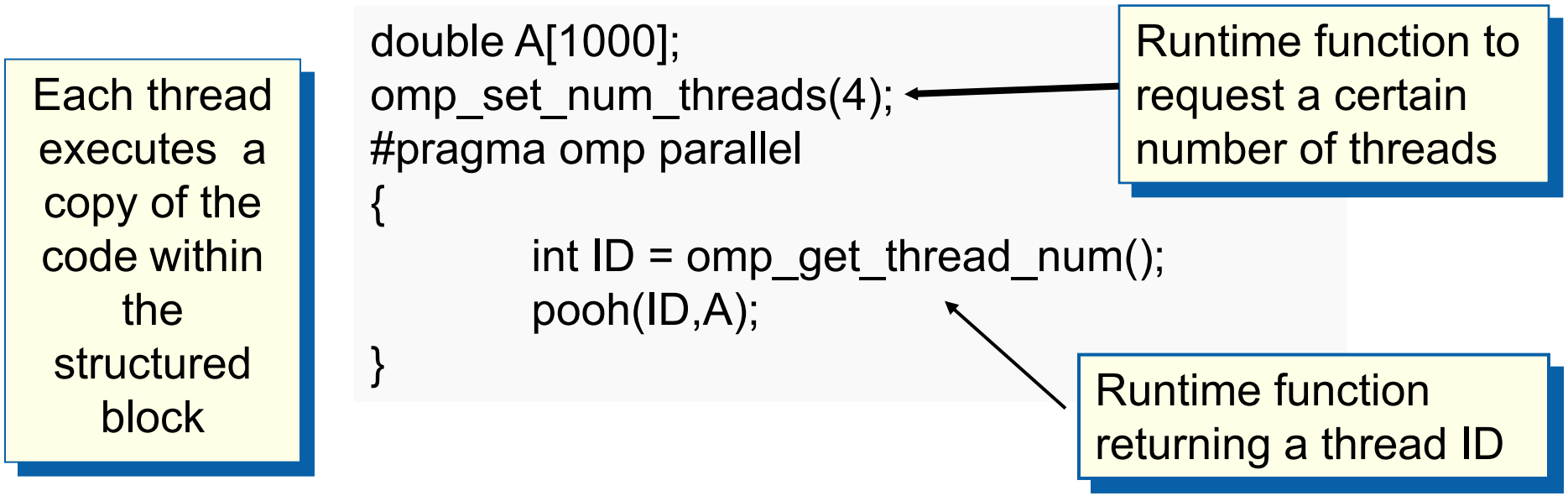
Fork-Join Parallelism:

- Initial thread spawns a team of threads as needed.
- Parallelism added incrementally until performance goals are met, i.e., the sequential program evolves into a parallel program.



Thread Creation: Parallel Regions

- You create threads in OpenMP with the parallel construct.
- For example, to create a 4 thread Parallel region:

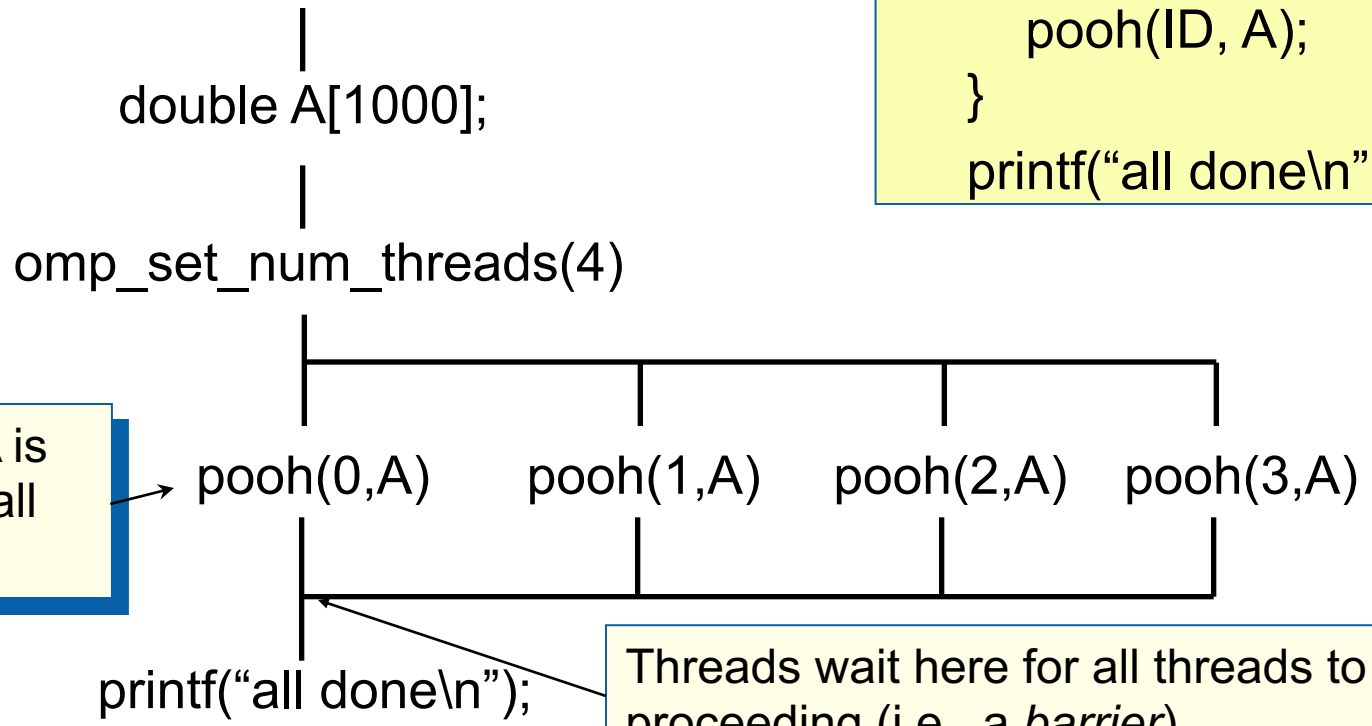


- Each thread calls pooh(ID,A) for ID = 0 to 3

Thread Creation: Parallel Regions Example

- Each thread executes the same code redundantly.

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
    int ID = omp_get_thread_num();
    pooh(ID, A);
}
printf("all done\n");
```



A single copy of A is shared between all threads.

Threads wait here for all threads to finish before proceeding (i.e., a *barrier*)

Thread creation: How many threads did you actually get?

- Request a number of threads with omp_set_num_threads()

- The number requested may not be the number you actually get.
  - An implementation may silently give you fewer threads than you requested.
  - Once a team of threads has launched, it will not be reduced.

Each thread executes a copy of the code within the structured block

```
double A[1000];
omp_set_num_threads(4);
#pragma omp parallel
{
        int ID      = omp_get_thread_num();
        int nthrds = omp_get_num_threads();
        pooh(ID,A);
}
```

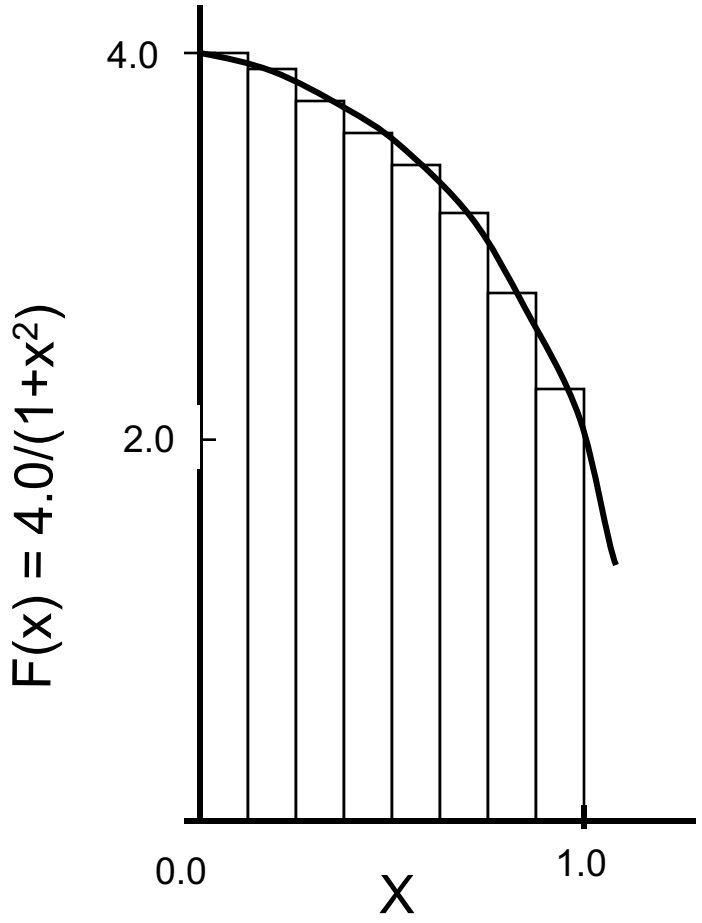
Runtime function to request a certain number of threads

Runtime function to return actual number of threads in the team

- Each thread calls pooh(ID,A) for ID = 0 to nthrds-1

An Interesting Problem to Play With

Numerical Integration



Mathematically, we know that:

$$\int_0^1 \frac{4.0}{(1+x^2)}\,dx = \pi$$

We can approximate the integral as a sum of N rectangles:

$$\sum_{i=0}^{N} F(x_i)\Delta x = \Delta x \sum_{i=0}^{N} F(x_i) \approx \pi$$

Where each rectangle has width Δx and height $F(x_i)$ at the middle of interval i.

Serial PI Program

```
static long num_steps = 100000;
double step;
int main ()
{       double x, pi, sum = 0.0;

        step = 1.0/(double) num_steps;

        for (int i=0;i< num_steps; i++){
                x = (i+0.5)*step;
                sum = sum + 4.0/(1.0+x*x);
        }
        pi = step * sum;
}
```

See hands-on/openmp/pi.c

Serial PI Program

```
#include <omp.h>
static long num_steps = 100000;
double step;
int main ()
{       double x, pi, sum = 0.0;

        step = 1.0/(double) num_steps;
        double tdata = omp_get_wtime();
        for (int i=0;i< num_steps; i++){
                x = (i+0.5)*step;
                sum = sum + 4.0/(1.0+x*x);
        }
        pi = step * sum;
        tdata = omp_get_wtime() - tdata;
        printf(" pi = %f in %f secs\n",pi, tdata);
}
```

The library routine get_omp_wtime() is used to find the elapsed "wall time" for blocks of code

See hands-on/openmp/pi.c

Exercise: the Parallel Pi Program

- Create a parallel version of the pi program using a parallel construct:

  #pragma omp parallel

- Pay close attention to shared versus private variables.
- In addition to a parallel construct, you will need the runtime library routines
  - int omp_get_num_threads();
  - int omp_get_thread_num();
  - double omp_get_wtime();
  - omp_set_num_threads();

Number of threads in the team

Thread ID or rank

Time in seconds since a fixed point in the past

Request a number of threads in the team

Hints: the Parallel Pi Program

- Use a parallel construct:

  #pragma omp parallel

- The challenge is to:
  - divide loop iterations between threads (use the thread ID and the number of threads).
  - Create an accumulator for each thread to hold partial sums that you can later combine to generate the global sum.

- In addition to a parallel construct, you will need the runtime library routines
  - omp_set_num_threads();
  - int omp_get_num_threads();
  - int omp_get_thread_num();
  - double omp_get_wtime();

Example: A simple SPMD* pi program

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{    int i, nthreads;  double pi, sum[NUM_THREADS];
     step = 1.0/(double) num_steps;
     omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel
     {
            int i, id,numthrds;
            double x;
            id = omp_get_thread_num();
            numthrds = omp_get_num_threads();
            if (id == 0)   nthreads = numthrds;
              for (i=id, sum[id]=0.0;i< num_steps; i=i+numthrds) {
                        x = (i+0.5)*step;
                        sum[id] += 4.0/(1.0+x*x);
              }
     }
     for(i=0, pi=0.0;i<nthreads;i++) pi += sum[i] * step;
}
```

Promote scalar to an array dimensioned by number of threads to avoid race condition.

Only one thread should copy the number of threads to the global value to make sure multiple threads writing to the same address don't conflict.

This is a common trick in SPMD programs to create a **cyclic distribution** of loop iterations

*SPMD: Single Program Multiple Data

Example: A simple SPMD pi program … an alternative solution

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{    int i, nthreads;  double pi, sum[NUM_THREADS];
     step = 1.0/(double) num_steps;
     omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel
    {
            int i, id,numthrds, istart, iend;
            double x;
            id = omp_get_thread_num();
            numthrds = omp_get_num_threads();
            istart = id*(num_steps/numthrds );      iend=(id+1)*(num_steps/numthrds);
            if(id == (numthrds-1)) iend = num_steps;
            if (id == 0)   nthreads = numthrds;
              for (i=istart, sum[id]=0.0;i< iend; i++) {
                        x = (i+0.5)*step;
                        sum[id] += 4.0/(1.0+x*x);
              }
     }
     for(i=0, pi=0.0;i<nthreads;i++) pi += sum[i] * step;
}
```

This is a common trick in SPMD algorithms … it's a **blocked distribution** with one block per thread.

SPMD: Single Program Multiple Data

Results*

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{    int i, nthreads;  double pi, sum[NUM_THREADS];
     step = 1.0/(double) num_steps;
     omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel
    {
            int i, id,nthrds;
            double x;
            id = omp_get_thread_num();
            nthrds = omp_get_num_threads();
            if (id == 0)   nthreads = nthrds;
            for (i=id, sum[id]=0.0;i< num_steps; i=i+nthrds) {
                    x = (i+0.5)*step;
                    sum[id] += 4.0/(1.0+x*x);
            }
    }
    for(i=0, pi=0.0;i<nthreads;i++)pi += sum[i] * step;
}
```

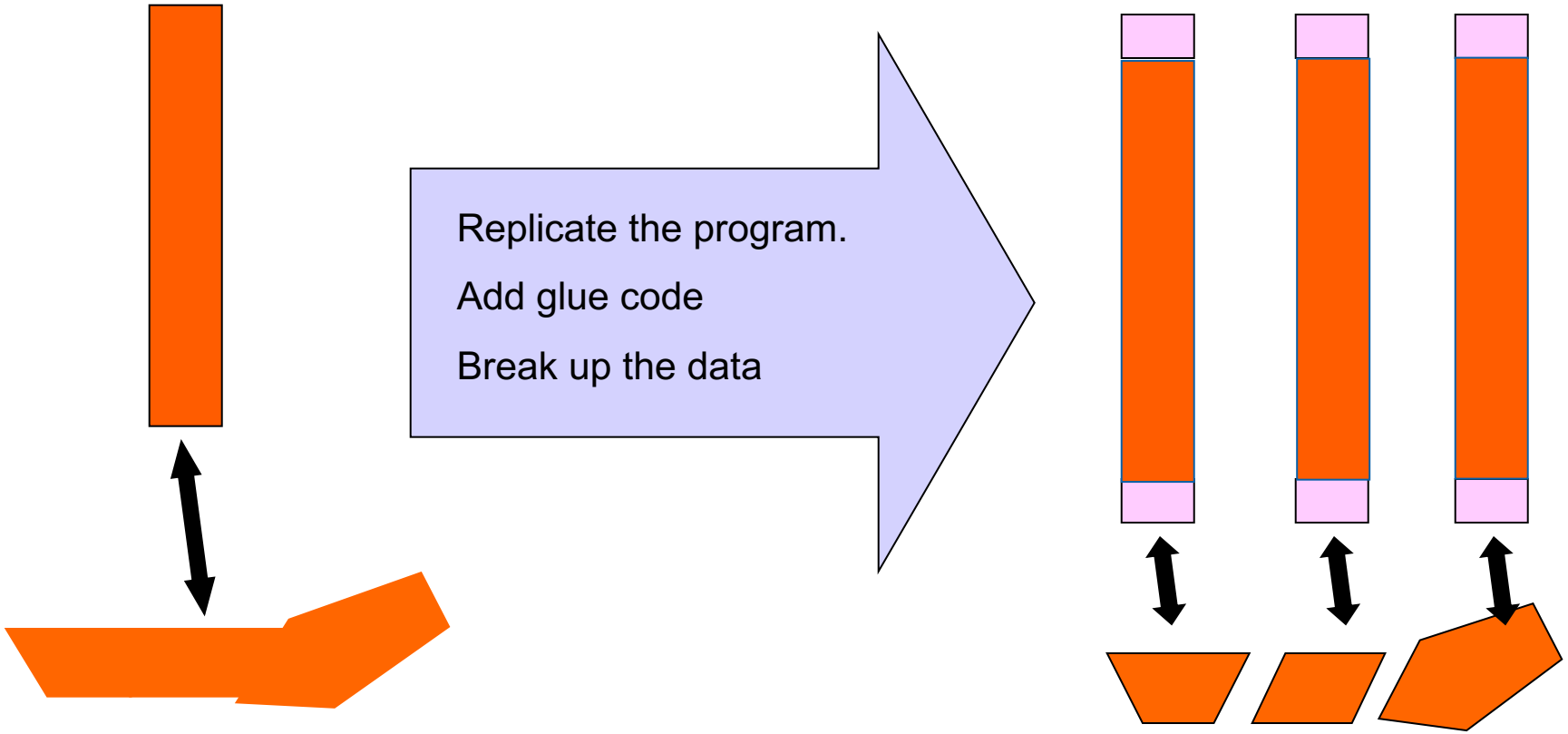
threads	1st SPMD*
1	1.86
2	1.03
3	1.08
4	0.97

Intel compiler (icpc) with default optimization level (O2) on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core™ i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

*SPMD: Single Program Multiple Data

SPMD: Single Program Multiple Data

- Run the same program on P processing elements where P can be arbitrarily large.



- Use the rank … an ID ranging from 0 to (P-1) … to select between a set of tasks and to manage any shared data structures.

MPI programs almost always use this pattern … it is probably the most commonly used pattern in the history of parallel programming.

A brief digression to talk about performance issues in parallel programs

Consider performance of parallel programs

Compute N independent tasks on one processor

Load Data | Compute T_1 | … | Compute T_N | Consume Results

$$Time_{seq}(1) = T_{load} + N*T_{task} + T_{consume}$$

Compute N independent tasks with P processors

Load Data

Compute T_1

…

Compute T_N

Consume Results

Ideally Cut runtime by ~1/P

(Note: Parallelism only speeds-up the concurrent part)

$$Time_{par}(P) = T_{load} + (N/P)*T_{task} + T_{consume}$$

Talking about performance

- Speedup: the increased performance from running on P processors.

$$S(P) = \frac{Time_{seq}(1)}{Time_{par}(P)}$$

- Perfect Linear Speedup: happens when no parallel overhead and algorithm is 100% parallel.

$$S(P) = P$$

- Super-linear Speedup: typically due to cache effects … i.e. as P grows, aggregate cache size grows so more of the problem fits in cache

$$S(P) > P$$

Amdahl's Law

- What is the maximum speedup you can expect from a parallel program?

- Approximate the runtime as a part that can be sped up with additional processors and a part that is fundamentally serial.

$$Time_{par}(P) = (serial\_fraction + \frac{parallel\_fraction}{P}) * Time_{seq}$$

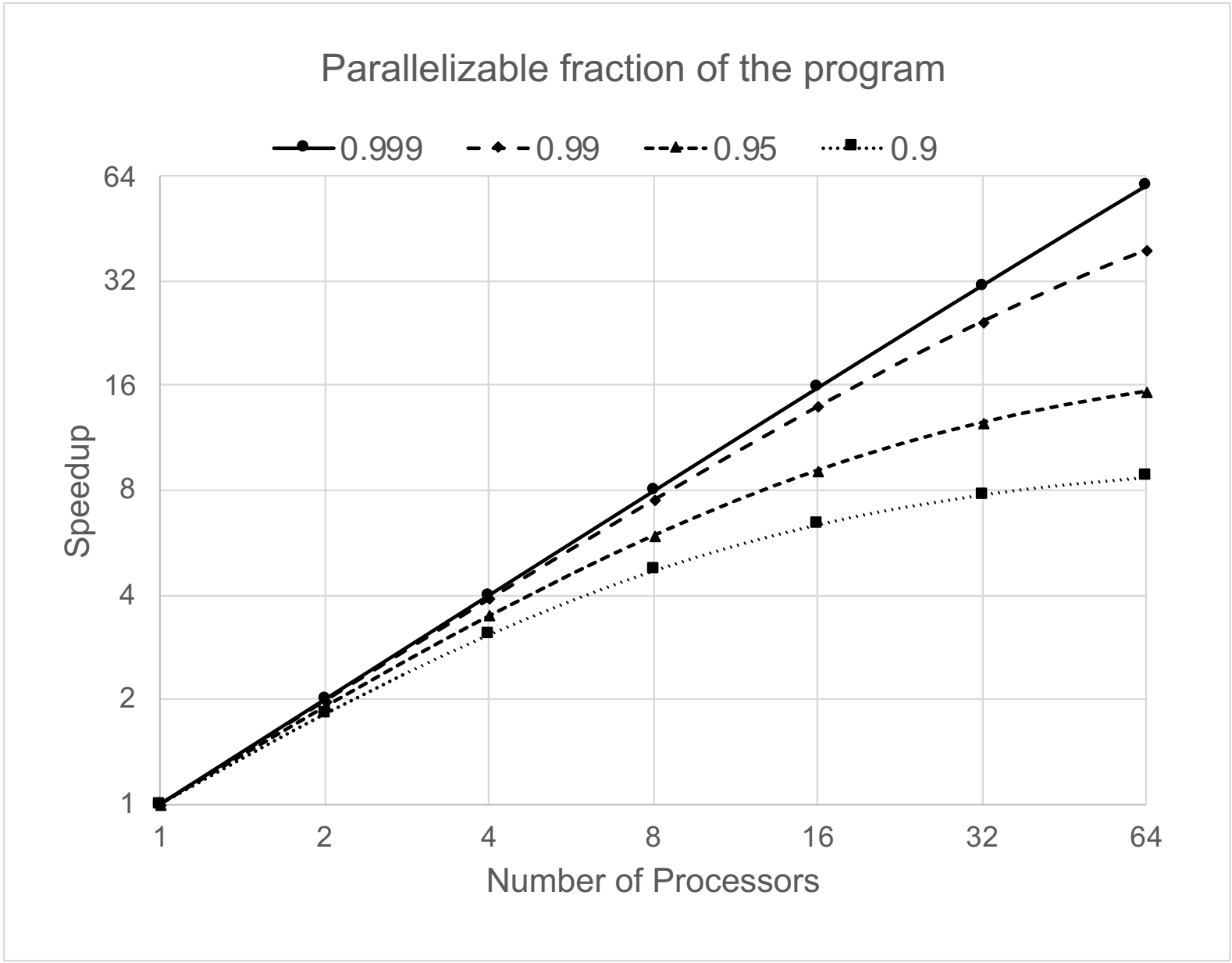
- If the serial fraction is α and the parallel fraction is (1- α) then the speedup is:

$$S(P) = \frac{Time_{seq}}{Time_{par}(P)} = \frac{Time_{seq}}{(\alpha + \frac{1-\alpha}{P}) * Time_{seq}} = \frac{1}{\alpha + \frac{1-\alpha}{P}}$$

- If you had an unlimited number of processors: $P \to \infty$

- The maximum possible speedup is: $S = \frac{1}{\alpha}$ ← Amdahl's Law

Amdahl's Law


Parallelizable fraction of the program
0.999
0.99
0.95
0.9
64
32
16
8
4
2
1
Speedup
1
2
4
8
16
32
64
Number of Processors

So now you should understand my silly introduction slide.

Introduction

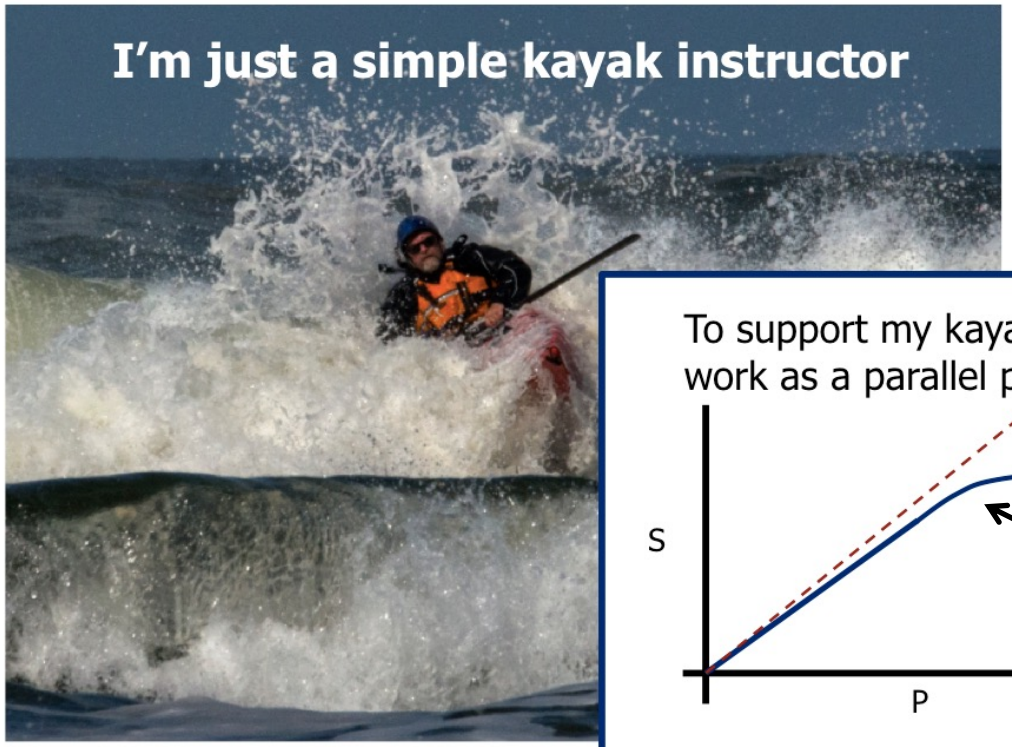


Photo © by Greg Clopton, 2014

To support my kayaking habit I work as a parallel programmer

Which means I know how to turn math into lines on a speedup plot

We measure our success as parallel programmers by how close we come to ideal linear speedup.

A good parallel programmer always figures out when you fall off the linear speedup curve and why that has occurred.

4

Exercise

- Go back to your parallel pi program and explore how well it scales with the number of threads.
- Can you explain your performance with Amdahl's law? If not what else might be going on?

  - int omp_get_num_threads();
  - int omp_get_thread_num();
  - double omp_get_wtime();
  - omp_set_num_threads();
  - export OMP_NUM_THREADS = N

An environment variable. Sets the default number of threads to request to N. Use this instead of requesting a number of threads with omp_set_thread_num(). Let's you change number of threads without recompiling code.

Results*

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{    int i, nthreads;  double pi, sum[NUM_THREADS];
     step = 1.0/(double) num_steps;
     omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel
    {
            int i, id,nthrds;
            double x;
            id = omp_get_thread_num();
            nthrds = omp_get_num_threads();
            if (id == 0)   nthreads = nthrds;
            for (i=id, sum[id]=0.0;i< num_steps; i=i+nthrds) {
                    x = (i+0.5)*step;
                    sum[id] += 4.0/(1.0+x*x);
            }
    }
    for(i=0, pi=0.0;i<nthreads;i++)pi += sum[i] * step;
}
```

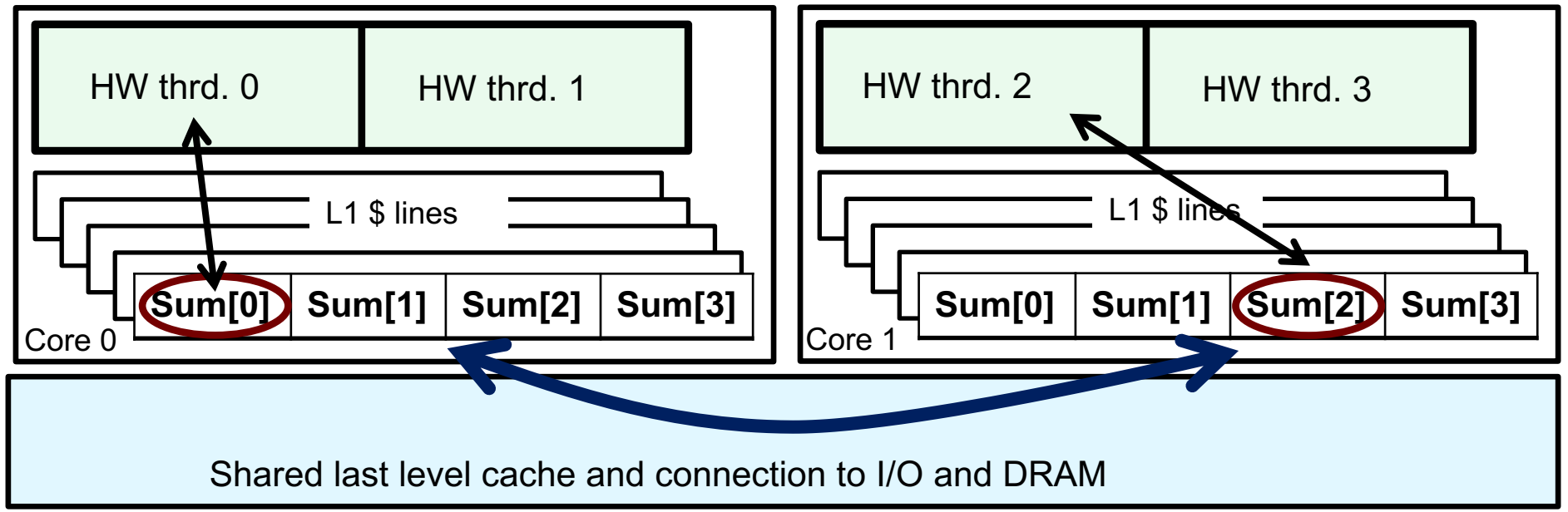
threads	1st SPMD*
1	1.86
2	1.03
3	1.08
4	0.97

Intel compiler (icpc) with default optimization level (O2) on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core™ i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

*SPMD: Single Program Multiple Data

Why Such Poor Scaling? False Sharing

- If independent data elements happen to sit on the same cache line, each update will cause the cache lines to “slosh back and forth” between threads … This is called **“false sharing”**.



- If you promote scalars to an array to support creation of an SPMD program, the array elements are contiguous in memory and hence share cache lines … Results in poor scalability.
- Solution: Pad arrays so elements you use are on distinct cache lines.

Example: Eliminate false sharing by padding the sum array

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
#define PAD 8        // assume 64 byte L1 cache line size
void main ()
{    int i, nthreads;  double pi, sum[NUM_THREADS][PAD] ;
     step = 1.0/(double) num_steps;
     omp_set_num_threads(NUM_THREADS);
     #pragma omp parallel
     {
          int i, id,nthrds;
          double x;
          id = omp_get_thread_num();
          nthrds = omp_get_num_threads();
          if (id == 0)    nthreads = nthrds;
          for (i=id, sum[id]=0.0;i< num_steps; i=i+nthrds) {
               x = (i+0.5)*step;
               sum[id][0] += 4.0/(1.0+x*x);
          }
     }
     for(i=0, pi=0.0;i<nthreads;i++)pi += sum[i][0] * step;
}
```

Pad the array so each sum value is in a different cache line

Results*: PI Program, Padded Accumulator

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
#define PAD 8        // assume 64 byte L1 cache line size
void main ()
{    int i, nthreads;  double pi, sum[NUM_THREADS][PAD] ;
     step = 1.0/(double) num_steps;
     omp_set_num_threads(NUM_THREADS);
     #pragma omp parallel
     {
          int i, id,nthrds;
          double x;
          id = omp_get_thread_num();
          nthrds = omp_get_num_threads();
          if (id == 0)    nthreads = nthrds;
          for (i=id, sum[id]=0.0;i< num_steps; i=i+nthrds) {
               x = (i+0.5)*step;
               sum[id][0] += 4.0/(1.0+x*x);
          }
     }
     for(i=0, pi=0.0;i<nthreads;i++)pi += sum[i][0] * step;
}
```

threads	1st SPMD	1st SPMD padded
1	1.86	1.86
2	1.03	1.01
3	1.08	0.69
4	0.97	0.53

*Intel compiler (icpc) with default optimization level (O2) on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core™ i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Outline

- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- Memory Model
- OpenMP stuff we didn't cover
- Recap

Synchronization

Synchronization is used to impose order constraints and to protect access to shared data

- High level synchronization included in the common core:
  - critical
  - barrier

- Other, more advanced, synchronization operations:
  - atomic
  - ordered
  - flush
  - locks (both simple and nested)

Synchronization: critical

- **Mutual exclusion**: Only one thread at a time can enter a **critical** region.

Threads wait their turn – only one thread at a time calls consume()

```
float  res;
#pragma omp parallel
{    float B;   int i, id, nthrds;
     id = omp_get_thread_num();
     nthrds = omp_get_num_threads();
     B =  big_SPMD_job(id, nthrds);
     #pragma omp critical
          res += consume (B);

}
```

Synchronization: barrier

- Barrier: a point in a program all threads much reach before any threads are allowed to proceed.
- It is a “stand alone” pragma meaning it is not associated with user code … it is an executable statement.

```
double Arr[8], Brr[8];          int numthrds;

omp_set_num_threads(8)

#pragma omp parallel

{    int id, nthrds;

     id = omp_get_thread_num();

     nthrds = omp_get_num_threads();

     if (id==0) numthrds = nthrds;

     Arr[id] = big_ugly_calc(id, nthrds);

#pragma omp barrier
     Brr[id] = really_big_and_ugly(id, nthrds, Arr);
}
```

Threads wait until all threads hit the barrier. Then they can go on.

Exercise

- In your first Pi program, you probably used an array to create space for each thread to store its partial sum.
- If array elements happen to share a cache line, this leads to false sharing.
  - Non-shared data in the same cache line so each update invalidates the cache line … in essence "sloshing independent data" back and forth between threads.

- Modify your "pi program" to avoid false sharing due to the partial sum array.

```
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
omp_set_num_threads();
#pragma parallel
#pragma critical
```

PI Program with False Sharing

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{    int i, nthreads;  double pi, sum[NUM_THREADS];
     step = 1.0/(double) num_steps;
     omp_set_num_threads(NUM_THREADS);
    #pragma omp parallel
    {
          int i, id,nthrds;
          double x;
          id = omp_get_thread_num();
          nthrds = omp_get_num_threads();
          if (id == 0)   nthreads = nthrds;
          for (i=id, sum[id]=0.0;i< num_steps; i=i+nthrds) {
               x = (i+0.5)*step;
               sum[id] += 4.0/(1.0+x*x);
          }
    }
    for(i=0, pi=0.0;i<nthreads;i++)pi += sum[i] * step;
}
```

Recall that promoting sum to an array made the coding easy, but led to false sharing and poor performance.

threads	1st SPMD
1	1.86
2	1.03
3	1.08
4	0.97

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core™ i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Example: Using a critical section to remove impact of false sharing

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{  int nthreads; double  pi=0.0;          step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
  #pragma omp parallel
  {
      int i, id, nthrds;    double x, sum;
      id = omp_get_thread_num();
      nthrds = omp_get_num_threads();
       if (id == 0)   nthreads = nthrds;
       for (i=id, sum=0.0;i< num_steps; i=i+nthrds) {
            x = (i+0.5)*step;
            sum += 4.0/(1.0+x*x);
       }
       #pragma omp critical
              pi += sum * step;
   }
}
```

Create a scalar local to each thread to accumulate partial sums.

No array, so no false sharing.

Sum goes “out of scope” beyond the parallel region … so you must sum it in here. Must protect summation into pi in a critical region so updates don’t conflict

Results*: pi program critical section

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{  int nthreads; double  pi=0.0;          step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
  #pragma omp parallel
  {
       int i, id, nthrds;    double x, sum;
       id = omp_get_thread_num();
       nthrds = omp_get_num_threads();
        if (id == 0)   nthreads = nthrds;
        for (i=id, sum=0.0;i< num_steps; i=i+nthrds) {
              x = (i+0.5)*step;
              sum += 4.0/(1.0+x*x);
         }
        #pragma omp critical
                pi += sum * step;
   }
}
```

threads	1st SPMD	1st SPMD padded	SPMD critical
1	1.86	1.86	1.87
2	1.03	1.01	1.00
3	1.08	0.69	0.68
4	0.97	0.53	0.53

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core™ i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Example: Using a critical section to remove impact of false sharing

```
#include <omp.h>
static long num_steps = 100000;        double step;
#define NUM_THREADS 2
void main ()
{  int nthreads; double  pi=0.0;          step = 1.0/(double) num_steps;
   omp_set_num_threads(NUM_THREADS);
  #pragma omp parallel
  {
       int i, id, nthrds;    double x, sum;
       id = omp_get_thread_num();
       nthrds = omp_get_num_threads();
        if (id == 0)   nthreads = nthrds;
        for (i=id, sum=0.0;i< num_steps; i=i+nthrds) {
              x = (i+0.5)*step;
              #pragma omp critical
                   sum += 4.0/(1.0+x*x);
         }
    }
}
```

What would happen if you put the critical section inside the loop?

Outline

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The Loop Worksharing Construct

- The loop worksharing construct splits up loop iterations among the threads in a team

```
#pragma omp parallel
{
    #pragma omp for
        for (I=0;I<N;I++){
            NEAT_STUFF(I);
        }
}
```

Loop construct name:

- C/C++: for
- Fortran: do

The loop control index I is made "private" to each thread by default.

Threads wait here until all threads are finished with the parallel loop before any proceed past the end of the loop

Loop Worksharing Construct

A motivating example

Sequential code

```
for(i=0;i<N;i++)   { a[i] = a[i] + b[i];}
```

OpenMP parallel region

(SPMD Pattern)

```
#pragma omp parallel
{
        int id, i, Nthrds, istart, iend;
        id = omp_get_thread_num();
        Nthrds = omp_get_num_threads();
        istart = id * N / Nthrds;
        iend = (id+1) * (N / Nthrds);
        if (id == Nthrds-1)iend = N;
        for(i=istart;i<iend;i++)   { a[i] = a[i] + b[i];}
}
```

OpenMP parallel region and a worksharing for construct

```
#pragma omp parallel
#pragma omp for
        for(i=0;i<N;i++)   { a[i] = a[i] + b[i];}
```

Loop Worksharing Constructs: The schedule clause

- The schedule clause affects how loop iterations are mapped onto threads
  - **schedule(static [,chunk])**
    - Deal-out blocks of iterations of size “chunk” to each thread.
  - **schedule(dynamic[,chunk])**
    - Each thread grabs “chunk” iterations off a queue until all iterations have been handled.
- Example:
  - #pragma omp for schedule(dynamic, 10)

Schedule Clause	When To Use
STATIC	**Pre-determined and predictable by the programmer**
DYNAMIC	**Unpredictable, highly variable work per iteration**

Least work at runtime : scheduling done at compile-time

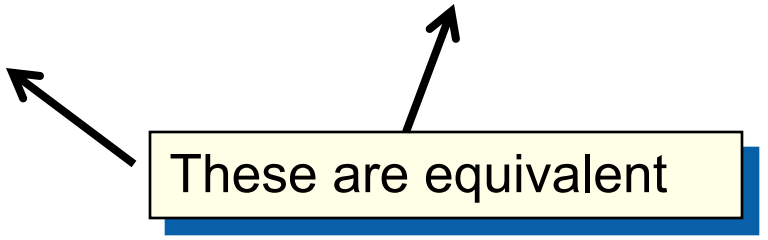
Most work at runtime : complex scheduling logic used at run-time

Combined Parallel/Worksharing Construct

- OpenMP shortcut: Put the “parallel” and the worksharing directive on the same line

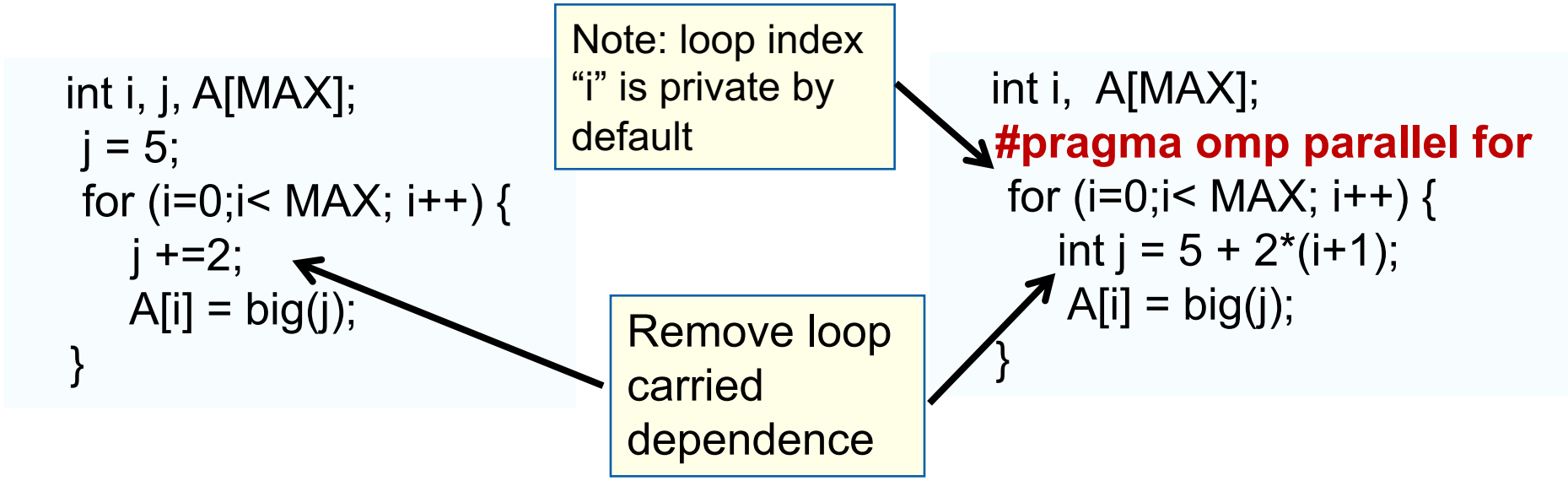
```
 double  res[MAX];  int i;
#pragma omp parallel
{
    #pragma omp for
    for (i=0;i< MAX; i++) {
        res[i] = huge();
    }
}
```

```
 double  res[MAX];  int i;
#pragma omp parallel for
    for (i=0;i< MAX; i++) {
        res[i] = huge();
    }
```



Working with loops

- Basic approach
  - Find compute intensive loops
  - Make the loop iterations independent ... So they can safely execute in any order without loop-carried dependencies
  - Place the appropriate OpenMP directive and test



Reduction

- How do we handle this case?

```
double  ave=0.0, A[MAX];
for (int i=0;i< MAX; i++) {
      ave + = A[i];
}
ave = ave/MAX;
```

- We are combining values into a single accumulation variable (ave) … there is a true dependence between loop iterations that can't be trivially removed.
- This is a very common situation … it is called a "reduction".
- Support for reduction operations is included in most parallel programming environments.

Reduction

- OpenMP reduction clause:

  reduction (op : list)

- Inside a parallel or a work-sharing construct:
  - A local copy of each list variable is made and initialized depending on the “op” (e.g. 0 for “+”).
  - Updates occur on the local copy.
  - Local copies are reduced into a single value and combined with the original global value.

- The variables in “list” must be shared in the enclosing parallel region.

```
double  ave=0.0, A[MAX];
#pragma omp parallel for reduction (+:ave)
 for (int i=0;i< MAX; i++) {
        ave + = A[i];
 }
 ave = ave/MAX;
```

Reduction … with arrays

- OpenMP reduction clause:

  reduction (op : list)

- Inside a parallel or a work-sharing construct:
  - A local copy of each list variable is made and initialized depending on the “op” (e.g. 0 for “+”).
  - Updates occur on the local copy.
  - Local copies are reduced into a single value and combined with the original global value.

- The variables in “list” must be shared in the enclosing parallel region.

```
 double  arr[N] = {0.0};
#pragma omp parallel for reduction(+:arr[0:N])
  for (int j=0;i< M; i++) {
       double val = A_Function(j);
       for (int i=0; i<N; i++){
           arr[i] += SomeFunction(i,val);
       }
   }
```

Indicates an array section with N elements starting at element 0

OpenMP: Reduction operands/initial-values

- Many different associative operands can be used with reduction:
- Initial values are the ones that make sense mathematically.

Operator	Initial value
+	0
*	1
-	0
min	Largest pos. number
max	Most neg. number

C/C++ only	
Operator	Initial value
&	~0
|	0
^	0
&&	1
||	0

Fortran Only	
Operator	Initial value
.AND.	.true.
.OR.	.false.
.NEQV.	.false.
.IEOR.	0
.IOR.	0
.IAND.	All bits on
.EQV.	.true.

OpenMP includes user defined reductions
(we just don't cover this topics here)

Exercise: PI with loops

- Go back to the serial pi program and parallelize it with a loop construct
- Your goal is to minimize the number of changes made to the serial program.

```
#pragma omp parallel
#pragma omp for
#pragma omp parallel for
#pragma omp for reduction(op:list)
#pragma omp critical
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
```

Example: PI with a loop and a reduction

```
#include <omp.h>
static long num_steps = 100000;        double step;
void main ()
{    int i;            double x, pi, sum = 0.0;
      step = 1.0/(double) num_steps;
      #pragma omp parallel
      {
          double x;
         #pragma omp for reduction(+:sum)
             for (i=0;i< num_steps; i++){
                    x = (i+0.5)*step;
                    sum = sum + 4.0/(1.0+x*x);
             }
       }
            pi = step * sum;
}
```

Create a team of threads … without a parallel construct, you'll never have more than one thread

Create a scalar local to each thread to hold value of x at the center of each interval

Break up loop iterations and assign them to threads … setting up a reduction into sum. Note … the loop index is local to a thread by default.

Example: PI with a loop and a reduction

```
#include <omp.h>
static long num_steps = 100000;        double step;
void main ()
{
    double pi, sum = 0.0;
     step = 1.0/(double) num_steps;

     #pragma omp parallel for reduction(+:sum)
     for (int i=0;i< num_steps; i++){
          double x = (i+0.5)*step;
          sum = sum + 4.0/(1.0+x*x);
     }
     pi = step * sum;
}
```

Using modern C style, we put declarations close to where they are used … which lets me use the parallel for construct.

Results*: PI with a loop and a reduction

- Original Serial pi program with 100000000 steps ran in 1.83 seconds.

Example: Pi with a loop and a reduction

```
#include <omp.h>
static long num_steps = 100000;        double step;
void main ()
{   int i;          double x, pi, sum = 0.0;
    step = 1.0/(double) num_steps;
    #pragma omp parallel
    {
        double x;
        #pragma omp for reduction(+:sum)
            for (i=0;i< num_steps; i++){
                    x = (i+0.5)*step;
                    sum = sum + 4.0/(1.0+x*x);
            }
    }
          pi = step * sum;
}
```

threads	1st SPMD	1st SPMD padded	SPMD critical	PI Loop
1	1.86	1.86	1.87	1.91
2	1.03	1.01	1.00	1.02
3	1.08	0.69	0.68	0.80
4	0.97	0.53	0.53	0.68

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core™ i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

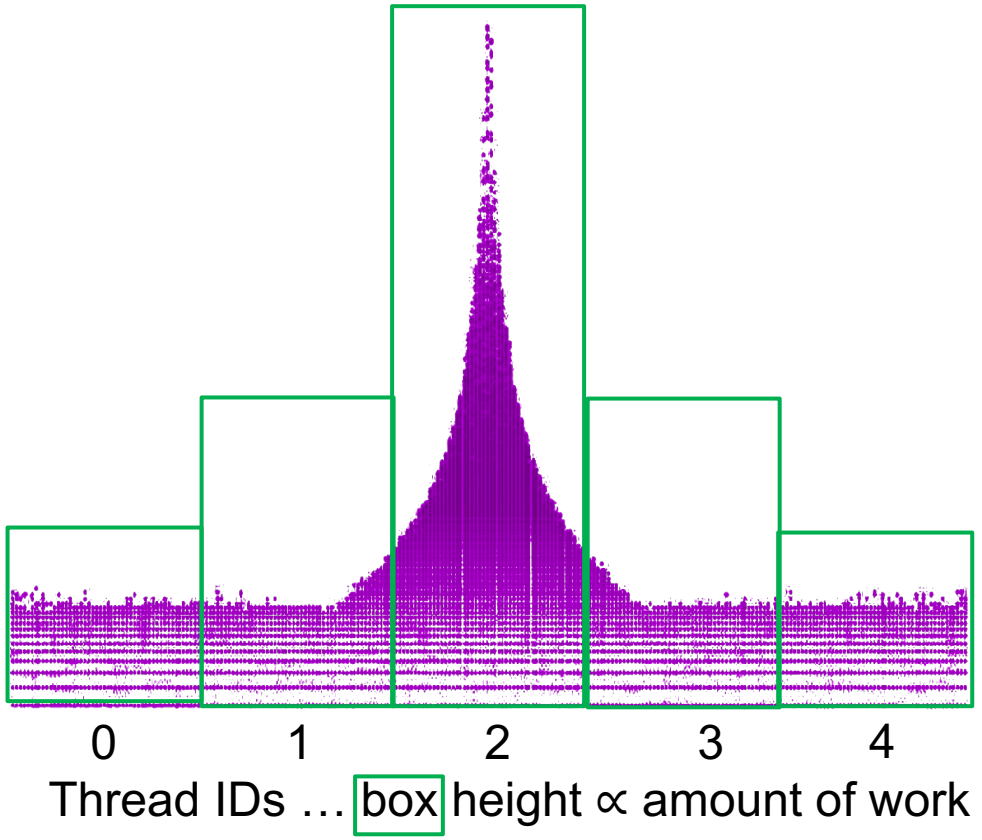
…. Let's pause a moment and consider one of the fundamental issues EVERY parallel programmer must grapple with

Load Balancing

- A parallel job isn't done until the last thread is finished

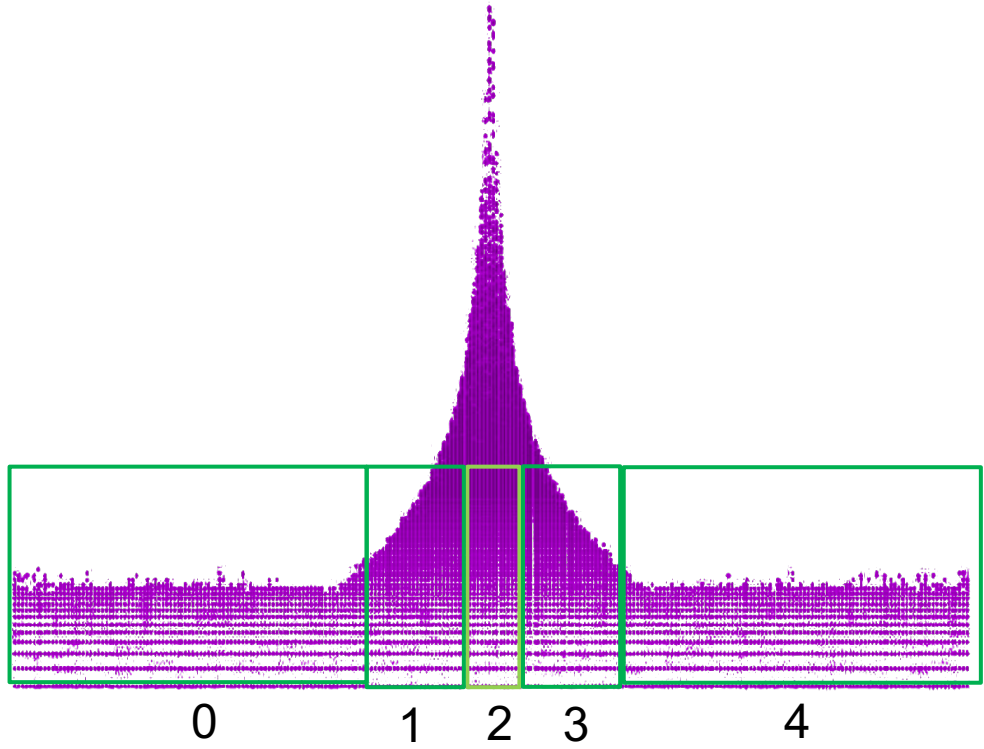
- Example: Partition a problem into equal sized chunks but for work that is unevenly distributed spatially.
  - Thread 2 has MUCH more work. The uneven distribution of work will limit performance.

- A key part of parallel programming is to design how you partition the work between threads so every thread has about the same amount of work. This topic is referred to as *Load Balancing*.



Load Balancing

- A parallel job isn't done until the last thread is finished
- The work in our problem is unevenly distributed spatially.
- A key part of parallel programming is to design how you partition the work between threads so every thread has about the same amount of work.
- This topic is referred to as *Load Balancing*.
- In this case we adjusted the size of each chunk to equalize the work assigned to each thread.
  - Getting the right sized chunks for a variable partitioning (as done here) can be really difficult.

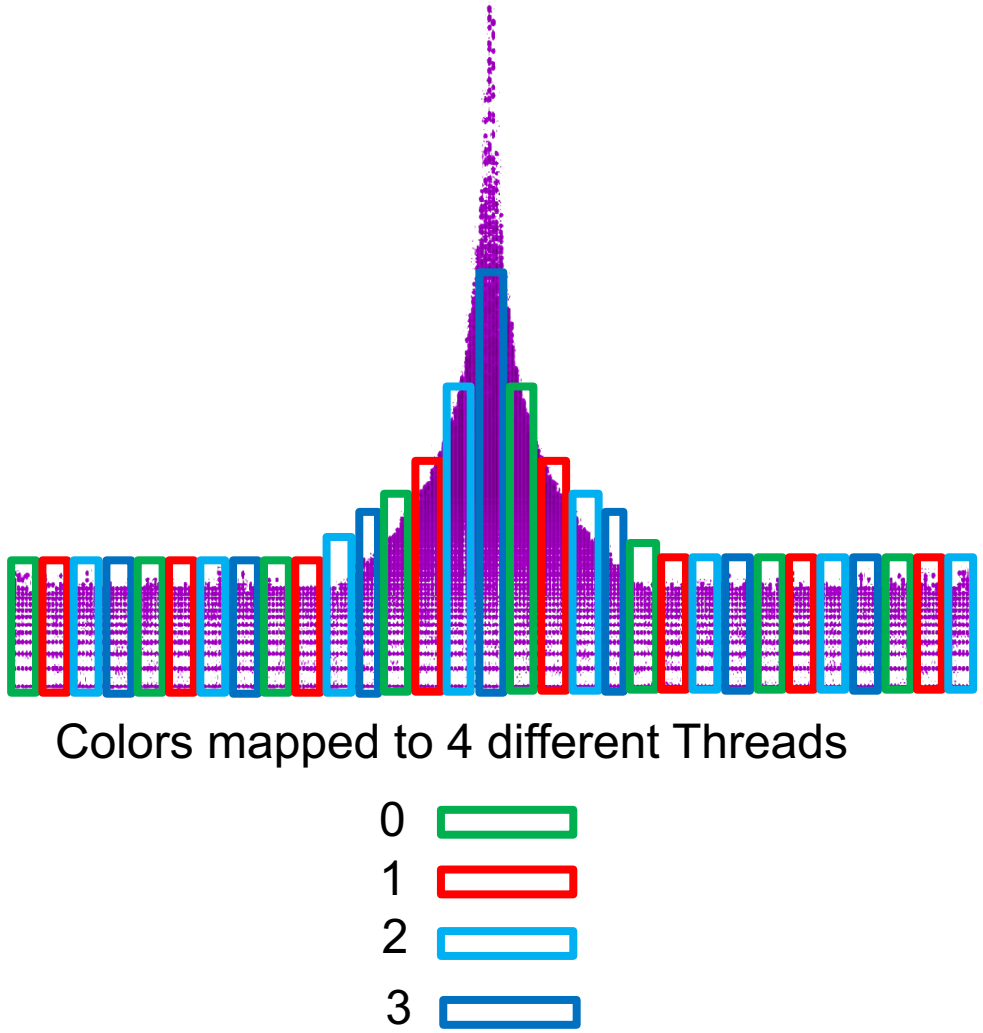


Thread IDs … box height ∝ amount of work

Load Balancing

- A parallel job isn't done until the last thread is finished

- An easier path to *Load Balancing*.
  - Over-decompose the problem into small, fine-grained chunks
  - Spread the chunks out among the threads (in this case using a cyclic distribution)
  - The work is spread out and statistically, you are likely to get a good distribution of work

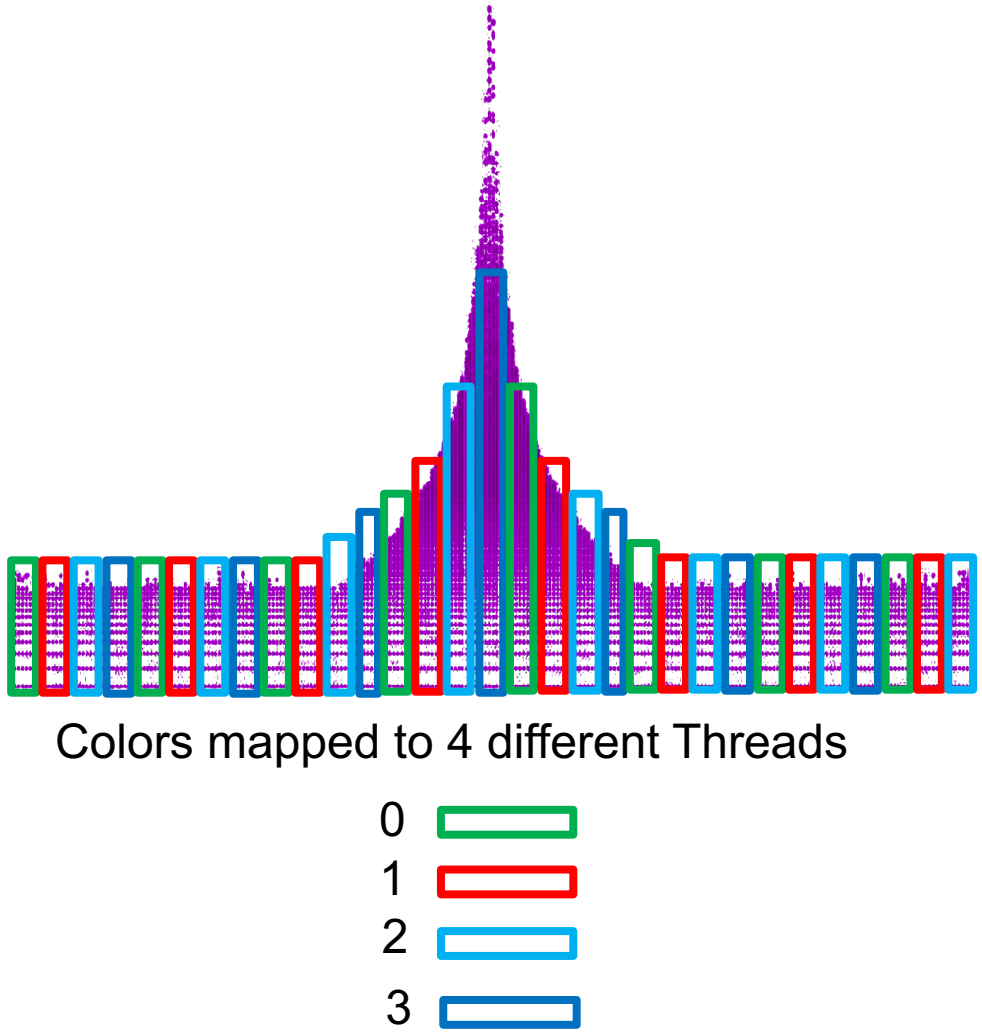


Load Balancing

- A parallel job isn't done until the last thread is finished

- An easier path to *Load Balancing*.
  - Over-decompose the problem into small, fine-grained chunks
  - Spread the chunks out among the threads (in this case using a cyclic distribution)
  - The work is spread out and statistically, you are likely to get a good distribution of work

- Vocabulary review
  - **Load Balancing** … giving each thread work sized so all threads take the same amount of time
  - **Partitioning** or **decomposition** … breaking up the problem domain into partitions (or chunks) and assigning different partitions to different threads.
  - **Granularity** … the size of the block of work. Find grained (small chunks) vs coarse grained (large chunks)
  - **Over-decomposition** … when you decompose your problem into partitions such that there are many more partitions than threads to do the work



Loop Worksharing Constructs: The schedule clause

- The schedule clause affects how loop iterations are mapped onto threads
  - **schedule(static [,chunk])**
    - Deal-out blocks of iterations of size “chunk” to each thread.
  - **schedule(dynamic[,chunk])**
    - Each thread grabs “chunk” iterations off a queue until all iterations have been handled.
- Example:
  - #pragma omp for schedule(dynamic, 10)

Schedule Clause	When To Use
STATIC	**Pre-determined and predictable by the programmer**
DYNAMIC	**Unpredictable, highly variable work per iteration**

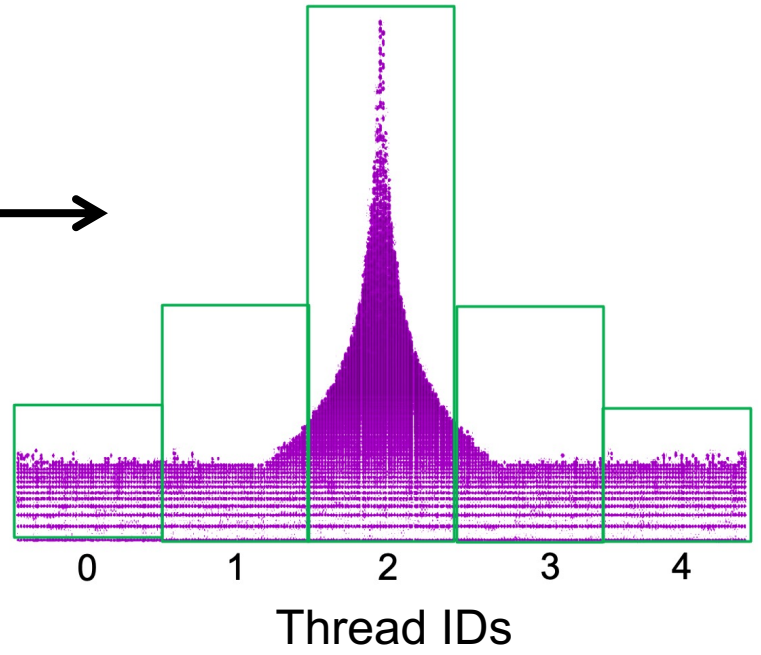
Least work at runtime : scheduling done at compile-time

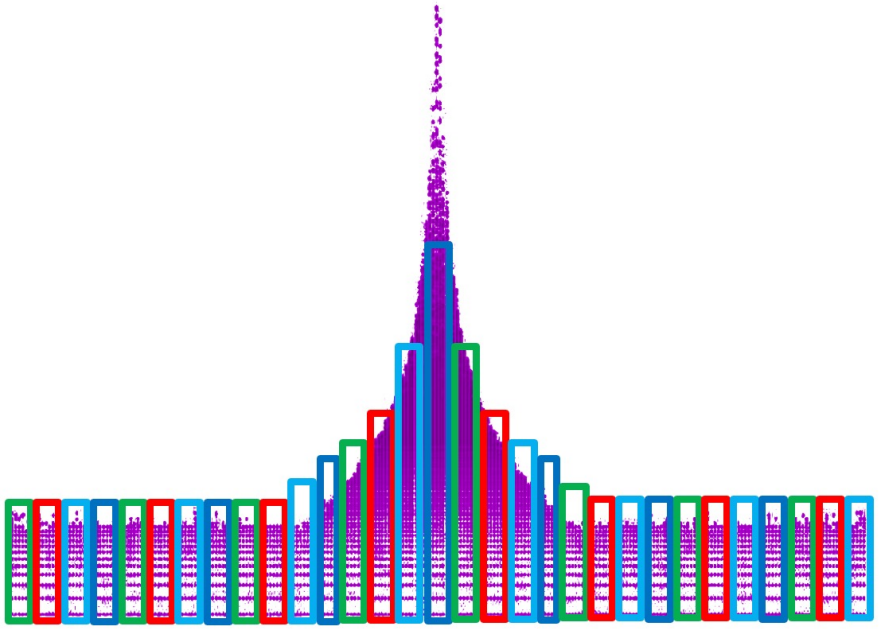
Most work at runtime : complex scheduling logic used at run-time

Loop Worksharing Constructs: The schedule clause

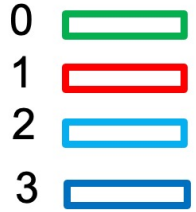
- The schedule clause … most common cases:

#pragma omp parallel for schedule (static)





Colors mapped to 4 different Threads



Int small = 8; // loop iterations, i.e., width of boxes in the figure

#pragma omp parallel for schedule (static, small)

We'll finish with loops by looking one more time at synchronization overhead

The nowait clause

- Barriers are really expensive. You need to understand when they are implied and how to skip them when it's safe to do so.

```
double A[big], B[big], C[big];

#pragma omp parallel
{
        int id=omp_get_thread_num();
        A[id] = big_calc1(id);
#pragma omp barrier
#pragma omp for
        for(i=0;i<N;i++){C[i]=big_calc3(i,A);}
#pragma omp for nowait
        for(i=0;i<N;i++){ B[i]=big_calc2(C,  i); }
        A[id] = big_calc4(id);
}
```

implicit barrier at the end of a for worksharing construct

implicit barrier at the end of a parallel region

no implicit barrier due to nowait

Outline

- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- Memory Model
- OpenMP stuff we didn't cover
- Recap

Data Environment: Default storage attributes

- Shared memory programming model:
  - Most variables are shared by default
- Global variables are SHARED among threads
  - Fortran: COMMON blocks, SAVE variables, MODULE variables
  - C: File scope variables, static
  - Both: dynamically allocated memory (ALLOCATE, malloc, new)
- But not everything is shared...
  - Stack variables in subprograms(Fortran) or functions(C) called from parallel regions are PRIVATE
  - Automatic variables within a statement block are PRIVATE.

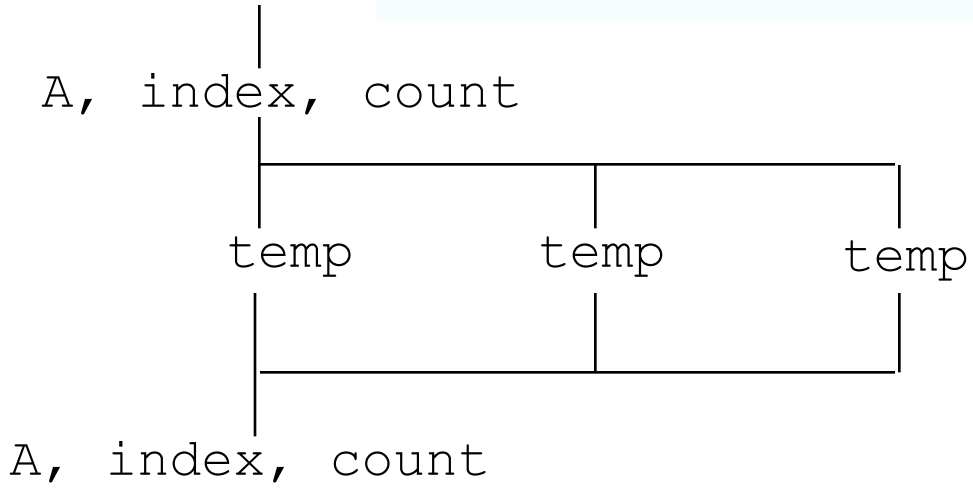
Data Sharing: Examples

```
double A[10];
int main() {
int index[10];
#pragma omp parallel
    work(index);
printf("%d\n", index[0]);
}
```

```
extern double A[10];
void work(int *index) {
  double temp[10];
  static int count;
  ...
}
```

A, index and count are shared by all threads.

temp is local to each thread



Data Sharing: Changing storage attributes

- One can selectively change storage attributes for constructs using the following clauses (note: ***list*** is a comma-separated list of variables)
  - **shared(list)**
  - **private(list)**
  - **firstprivate(list**)
- These can be used on **parallel** and **for** constructs … other than **shared** which can only be used on a **parallel** construct

- Force the programmer to explicitly define storage attributes
  - **default (none)**

default() can only be used on parallel constructs

Data Sharing: Private clause

- private(var) creates a new local copy of var for each thread.

```
int N = 1000;
extern void init_arrays(int N, double *A, double *B, double *C);


void example () {
     int i, j;
     double A[N][N], B[N][N], C[N][N];
     init_arrays(N, *A, *B, *C);


     #pragma omp parallel for private(j)
     for (i = 0; i < 1000; i++)
          for( j = 0; j<1000; j++)
               C[i][j] = A[i][j] + B[i][j];
}
```

OpenMP makes the loop control index on the parallel loop (i) private by default … but not for the second loop (j)

Data Sharing: Private clause

- private(var) creates a new local copy of var for each thread.
  - The value of the private copies is uninitialized
  - The value of the original variable is unchanged after the region

```
void wrong() {
      int tmp = 0;
#pragma omp parallel for private(tmp)
      for (int j = 0; j < 1000; ++j)
            tmp += j;
      printf("%d\n", tmp);
}
```

tmp was not initialized

When you need to refer to the variable tmp that exists prior to the construct, we call it the **original variable**.

tmp is 0 here

Firstprivate clause

- Variables initialized from a shared variable
- C++ objects are copy-constructed

```
incr = 0;
#pragma omp parallel for firstprivate(incr)
for (i = 0; i <= MAX; i++) {
        if ((i%2)==0) incr++;
        A[i] = incr;
}
```

Each thread gets its own copy of incr with an initial value of 0

Exercise: Mandelbrot set area

- The supplied program (mandel.c) computes the area of a Mandelbrot set.
- The program has been parallelized with OpenMP, but we were lazy and didn't do it right.
- Find and fix the errors.
- Once you have a working version, try to optimize the program.

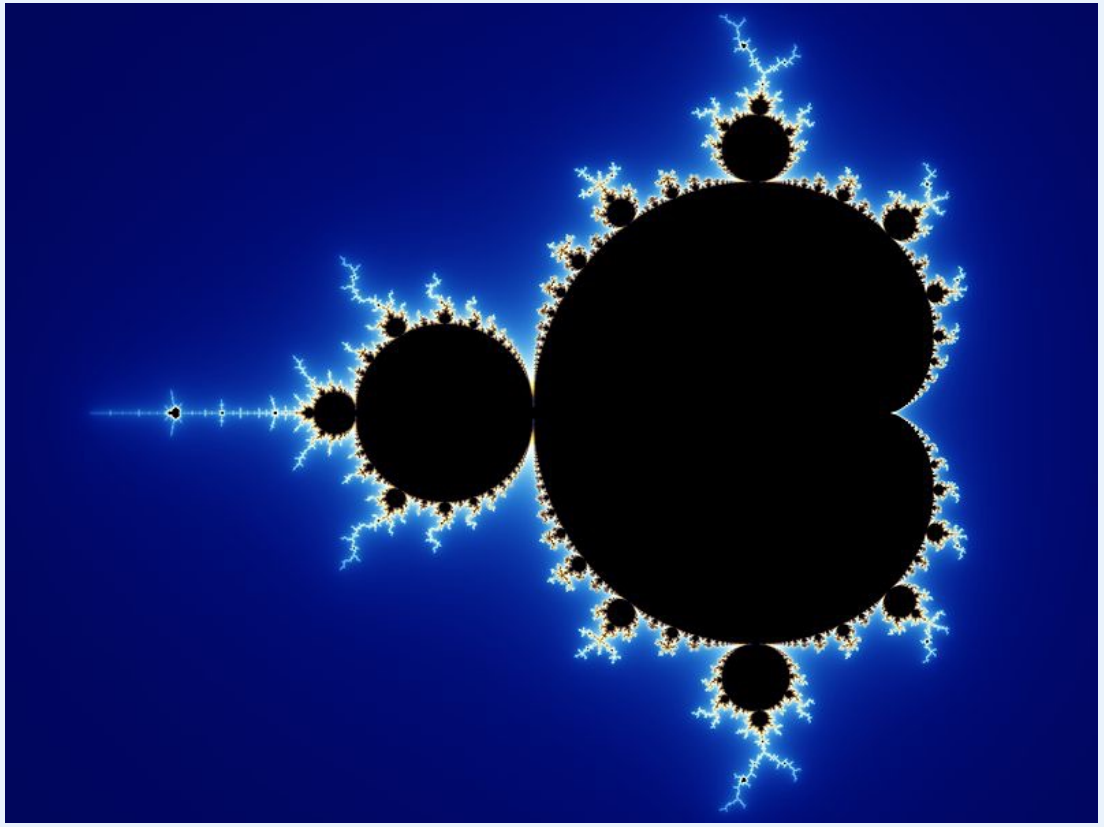


Image Source: Created by Wolfgang Beyer with the program Ultra Fractal 3. - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=321973

The Mandelbrot set … The points, c, for which the following iterative map converges

$$z_{n+1} = z_n^2 + c$$

With z_n and c as complex numbers and $z_0 = 0$.

```
#pragma omp parallel
#pragma omp for
#pragma omp parallel for
#pragma omp critical
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
```

```
#pragma omp parallel private (list)
#pragma omp parallel shared (list)
#pragma omp parallel firstprivate (list)
#pragma omp parallel default(none)
#pragma omp for reduction(op:list)
```

This exercise come from Mark Bull of EPCC (at University of Edinburgh)

The Mandelbrot Set Area Program (original code)

```
#include <omp.h>
# define NPOINTS 1000
# define MXITR 1000
void testpoint(double, double);
Int numoutside = 0;
int main(){
   int i, j;
   int num=0;
   double C_real, C_imag;
   double area, error, eps  = 1.0e-5;
#pragma omp parallel for private(eps)
   for (i=0; i<NPOINTS; i++) {
     for (j=0; j<NPOINTS; j++) {
       C_real = -2.0+2.5*(double)(i)/(double)(NPOINTS)+eps;
       C_imag = 1.125*(double)(j)/(double)(NPOINTS)+eps;
       testpoint(C_real, C_imag);
     }
   }
area=2.0*2.5*1.125*(double)(NPOINTS*NPOINTS-
numoutside)/(double)(NPOINTS*NPOINTS);
   error=area/(double)NPOINTS;
}
```

```
void testpoint(double C_real, double C_imag){
      double zr, zi;
      int iter;
      double temp;

      zr=C_real;     zi=C_imag;
      int numoutside = 0;
      for (iter=0; iter<MXITR; iter++){
        temp = (zr*zr)-(zi*zi)+C_real;
        zi = zr*zi*2+C_imag;
        zr = temp;
        if ((zr*zr+zi*zi)>4.0) {
              numoutside++;
        }
      }
      return 0;
}
```

The Mandelbrot Set Area Program

```
#include <omp.h>
# define NPOINTS 1000
# define MXITR 1000
void testpoint(double, double);
Int numoutside = 0;
int main(){
   int i, j;
   int num=0;
   double C_real, C_imag;
   double area, error, eps  = 1.0e-5;
#pragma omp parallel for private(j, C_real, C_imag)
   for (i=0; i<NPOINTS; i++) {
     for (j=0; j<NPOINTS; j++) {
       C_real = -2.0+2.5*(double)(i)/(double)(NPOINTS)+eps;
       C_imag = 1.125*(double)(j)/(double)(NPOINTS)+eps;
       testpoint(C_real, C_imag);
     }
   }
area=2.0*2.5*1.125*(double)(NPOINTS*NPOINTS-
numoutside)/(double)(NPOINTS*NPOINTS);
   error=area/(double)NPOINTS;
}
```

```
void testpoint(double C_real, double C_imag){
      double zr, zi;
      int iter;
      double temp;

      zr=C_real;     zi=C_imag;
      int numoutside = 0;
      for (iter=0; iter<MXITR; iter++){
        temp = (zr*zr)-(zi*zi)+C_real;
        zi = zr*zi*2+C_imag;
        zr = temp;
        if ((zr*zr+zi*zi)>4.0) {
          #pragma omp critical
              numoutside++;
        }
      }
      return 0;
}
```

- eps was not initialized … OK to leave it shared
- Make j, C_real, and C_imag private
- Protect updates of numoutside

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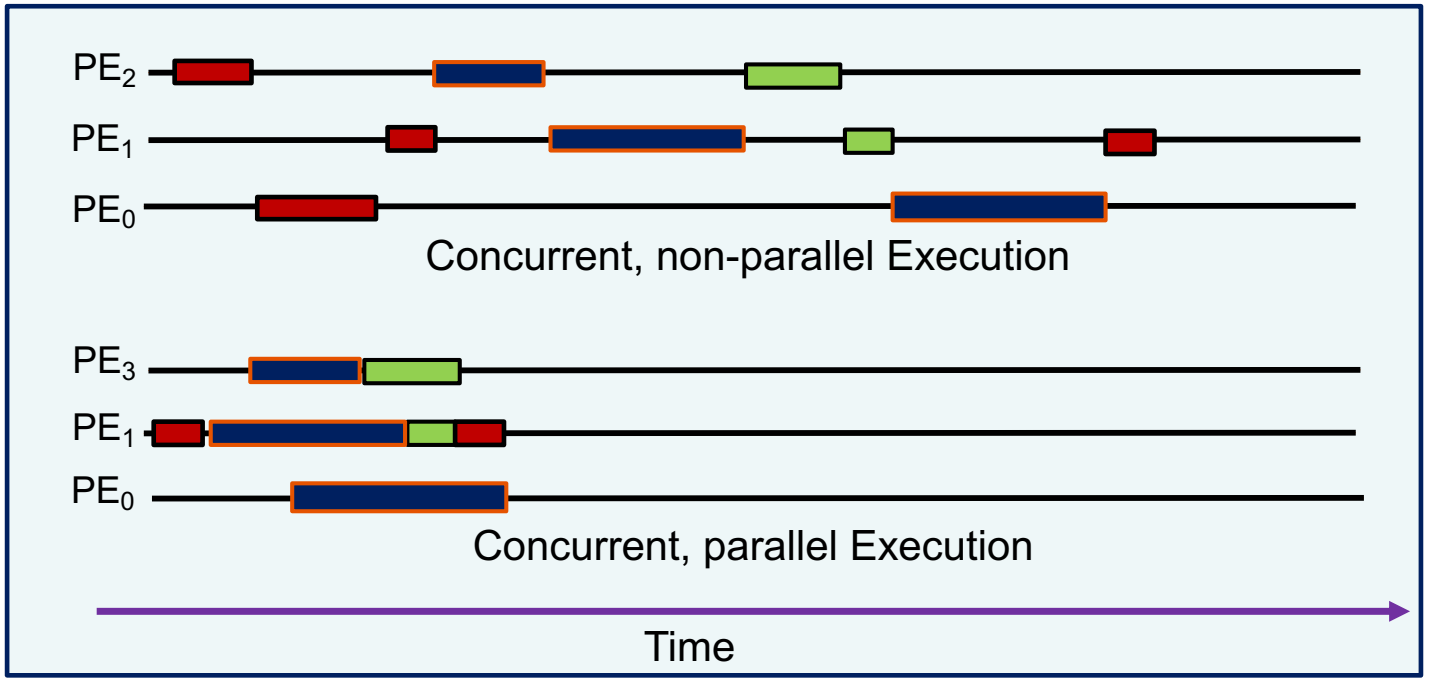
Concurrency vs. Parallelism

- Concurrency: A condition of a system in which multiple tasks are active and unordered. If **scheduled fairly**, they can be described as ***logically*** making **forward progress** at the same time.

- Parallelism: A condition of a system in which multiple tasks are **actually** making **forward progress** at the same time.



The fundamental execution model of Multithreading

A collection of active threads, scheduled fairly, that share an address space and execute **concurrently**.

PE = Processing Element

Figure from "An Introduction to Concurrency in Programming Languages" by J. Sottile, Timothy G. Mattson, and Craig E Rasmussen, 2010

Consider two threads: a producer/consumer pair

One thread **produces** a result that a different thread **consumes**

```
#include <stdio.h>
#include <omp.h>
#define COUNT 1000000
int main()
{
  int answer = 0, flag= 0,err=0;
  for (int i=0; i<COUNT; i++) {
    flag = 0;  answer=0;
    #pragma omp parallel shared(flag,answer) num_threads(2)
    {
      int id = omp_get_thread_num();
      if (id == 0) {
         answer = 42;
         flag = 1;
      }
      else if (id == 1){
         while (flag == 0)  { }
         if(answer!=42) err++;
      }
    }
  }
  return 0;
}
```

Thread zero produces the answer and then sets a flag to communicate the answer to another thread

Thread one “spins" in a while loop until the flag is non-zero which indicates that answer is available.

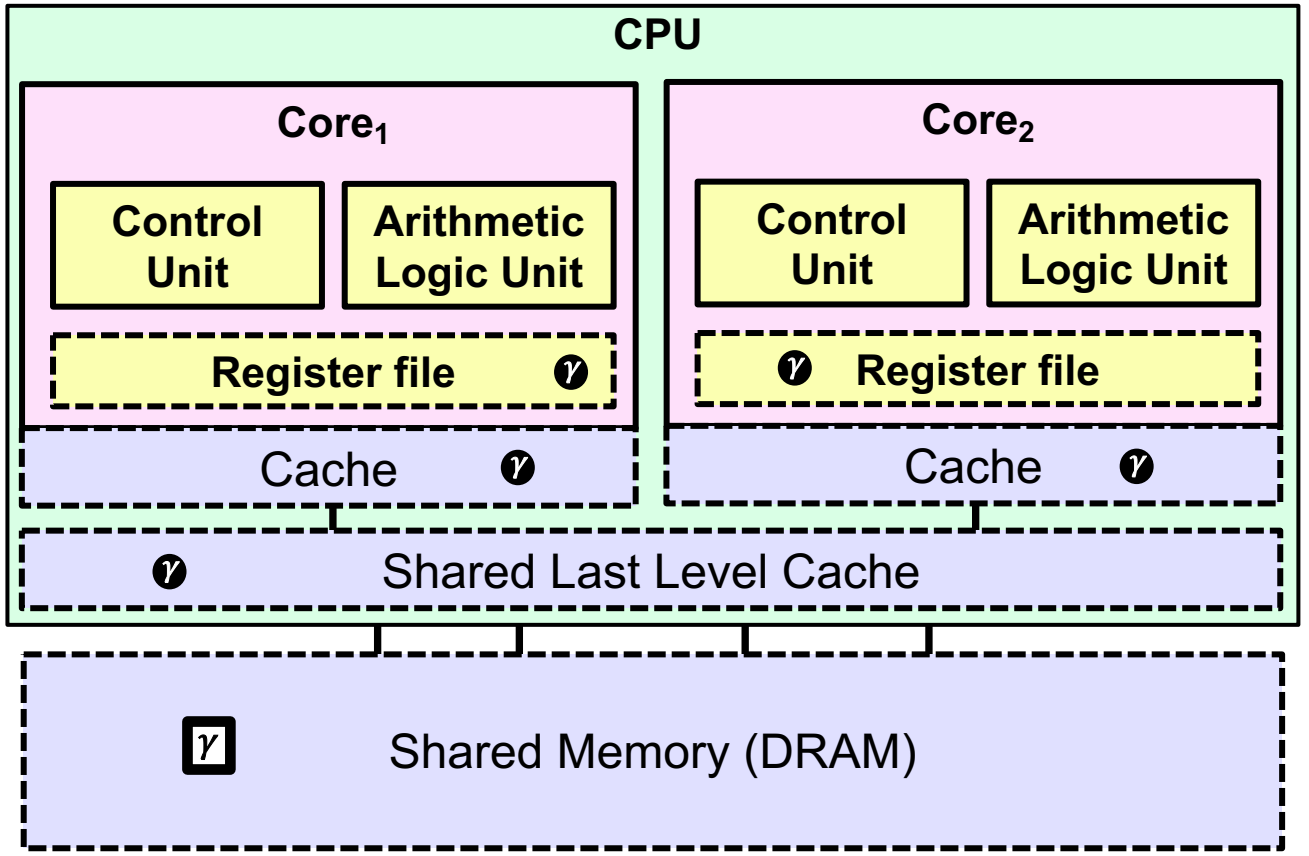
In the jargon of concurrent programming, this is called a “spin lock”

Put this in a file sync.c and compile as: **gcc –fopenmp –O3 sync.c**

The program went through a few loop iterations and then hangs …. Why?

Memory Models …

- A shared address space is a region of memory visible to the team of threads … multiple threads can read and write variables in the shared address space.
- Multiple copies of a variable (such as γ) may be present in memory, at various levels of cache, or in registers and they may ALL have different values.



- Which value of γ is the one a thread should see at any point in a computation?

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- A shared address space is a region of memory visible to the team of threads … multiple threads can read and write variables in the shared address space.
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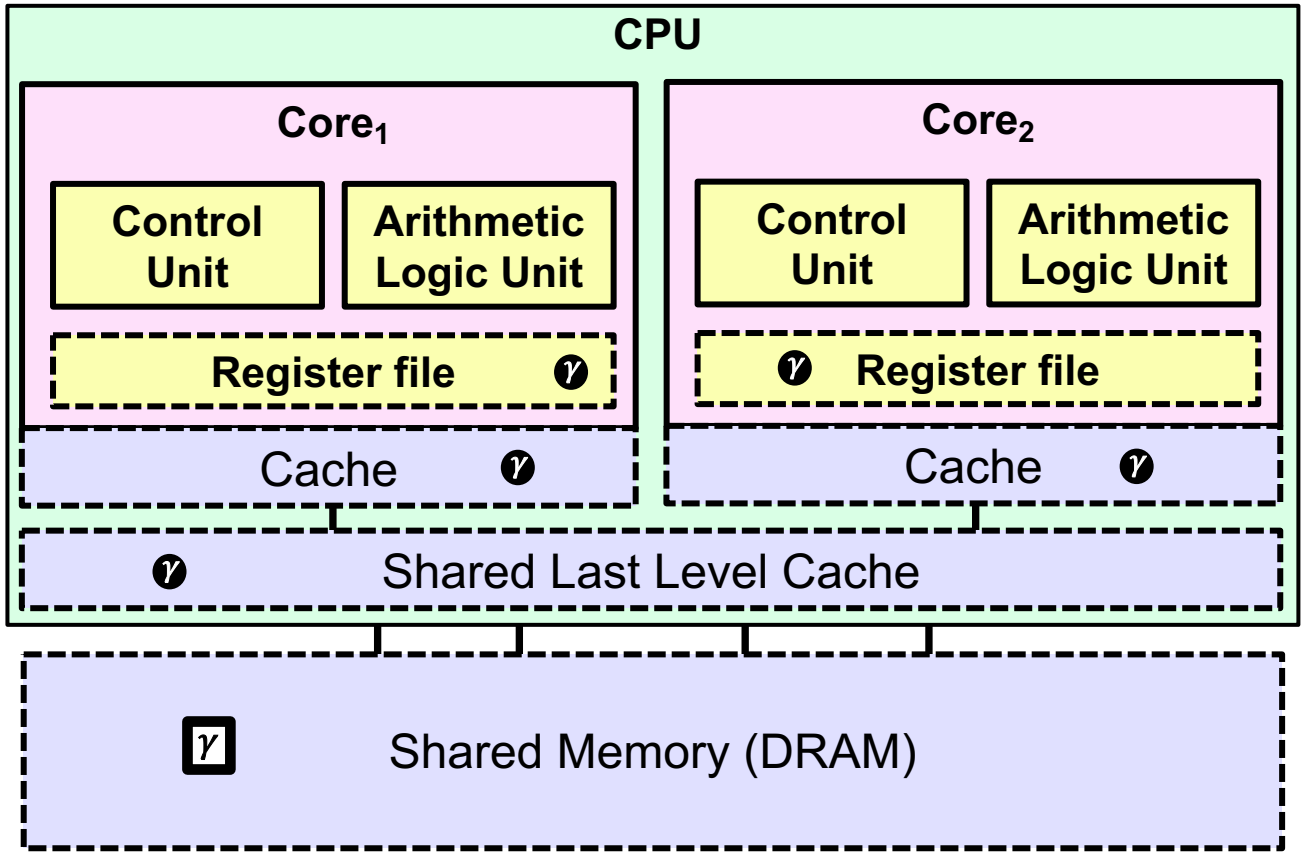


A memory consistency model (or "**memory model**" for short) provides the rules needed to answer this question.

- Which value of γ is the one a thread should see at any point in a computation?

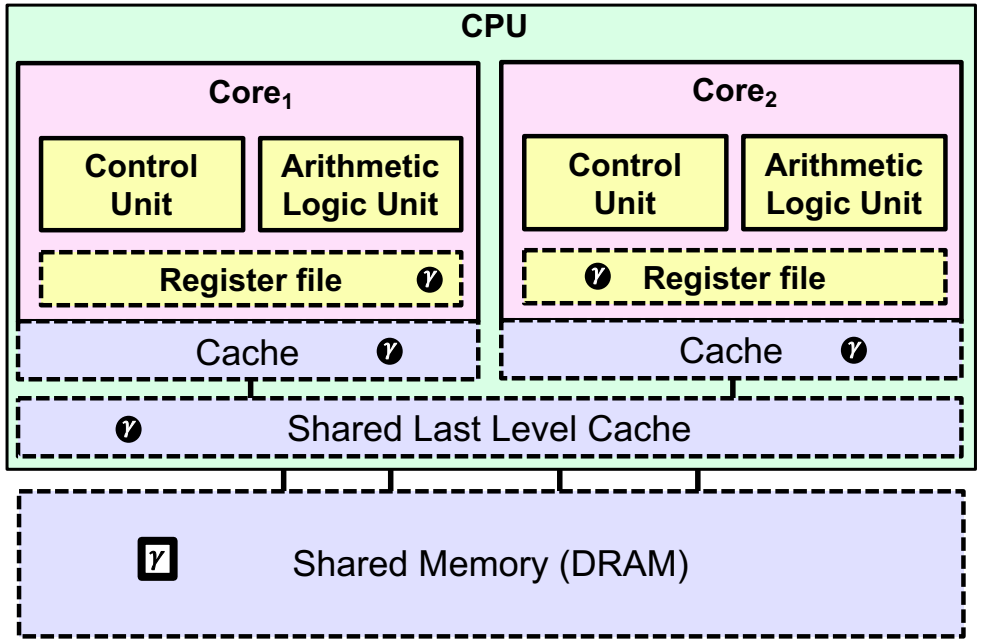
Memory Models …

- The fundamental issue is how do the values of variables across the memory hierarchy interact with the statements executed by two or more threads?
- Two options:

1. **Sequential Consistency**

- Threads execute and the associated loads/stores appear in some order defined by the semantically allowed interleaving of program statements.

- **All threads see the same interleaved order of loads and stores**



2. **Relaxed Consistency**

- Threads execute and the associated loads/stores appear in some order defined by the semantically allowed interleaving of program statements.

- **Threads may see different orders of loads and stores**

Most (if not all) multithreading programming models assume **relaxed consistency**. Maintaining sequential consistency across the full program-execution adds too much synchronization overhead.

Why did this program fail?

Two issues:

(1) Can thread 1 fail to see updates to **flag**?

(2) Can **flag** be 1 while **answer** is still 0?

```
#include <stdio.h>
#include <omp.h>
#define COUNT 1000000
int main()
{
  int answer = 0, flag= 0,err=0;
  for (int i=0; i<COUNT; i++) {
    flag = 0;  answer=0;
    #pragma omp parallel shared(flag,answer) num_threads(2)
    {
      int id = omp_get_thread_num();
      if (id == 0) {
         answer = 42;
         flag = 1;
      }
      else if (id == 1){
         while (flag == 0)  { }
         if(answer!=42) err++;
      }
    }
  }
  return 0;
}
```

The compiler can reorder statements, so **flag** is set to 1 before **answer** is set to **42**

Thread 1 can load **flag** from the register file. It may not even go to cache (let alone memory) to see an updated value.

Regardless of how the compiler orders stores to **answer** and **flag**, thread 1 may see a different order than thread 0

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Two issues:

(1) Can thread 1 fail to see updates to **flag**?

(2) Can **flag** be 1 while **answer** is still 0?

```
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#define COUNT 1000000
int main()
{
  int answer = 0, flag= 0,err=0;
  for (int i=0; i<COUNT; i++) {
    flag = 0;  answer=0;
    #pragma omp parallel shared(flag,answer) num_threads(2)
    {
      int id = omp_get_thread_num();
      if (id == 0) {
         answer = 42;
         flag = 1;
      }
      else if (id == 1){
         while (flag == 0)  { }
         if(answer!=42) err++;
      }
    }
  }
  return 0;
}
```

We need to enforce ordering constraints between the concurrent threads … we need to consider the memory model and put the right synchronization constructs in place.

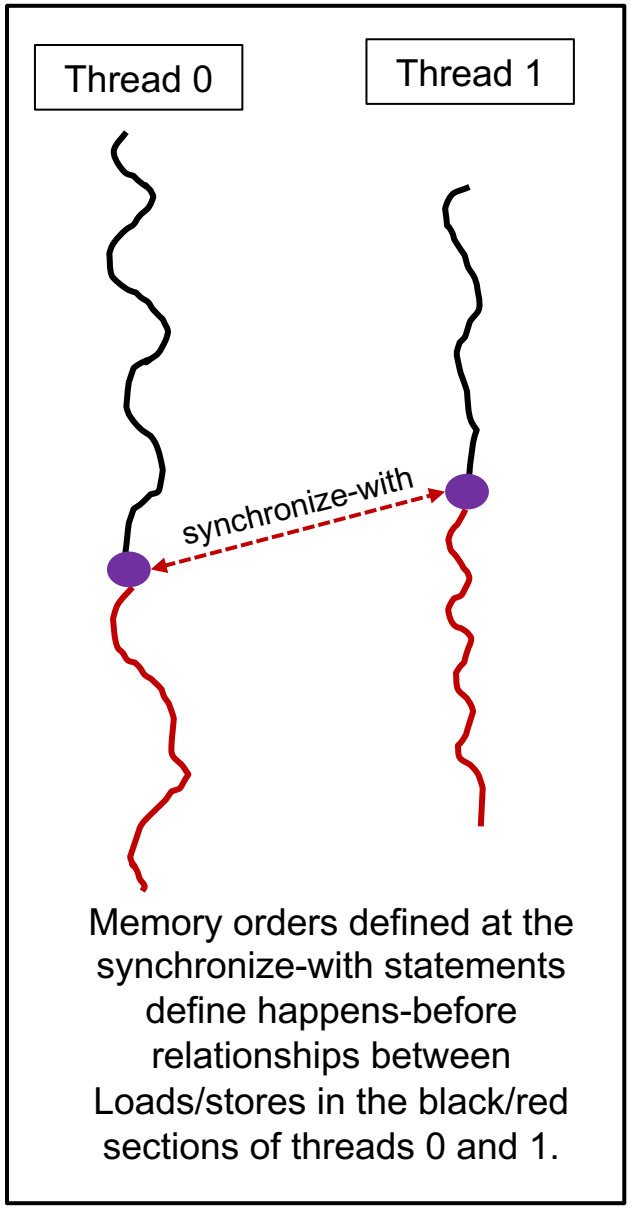
The compiler can reorder statements, so **flag** is set to 1 before **answer** is set to **42**

Thread 1 can load **flag** from the register file. It may not even go to cache (let alone memory) to see an updated value.

Regardless of how the compiler orders stores to **answer** and **flag**, thread 1 may see a different order than thread 0

Memory Models: *Happens-before* and *synchronized-with* relations

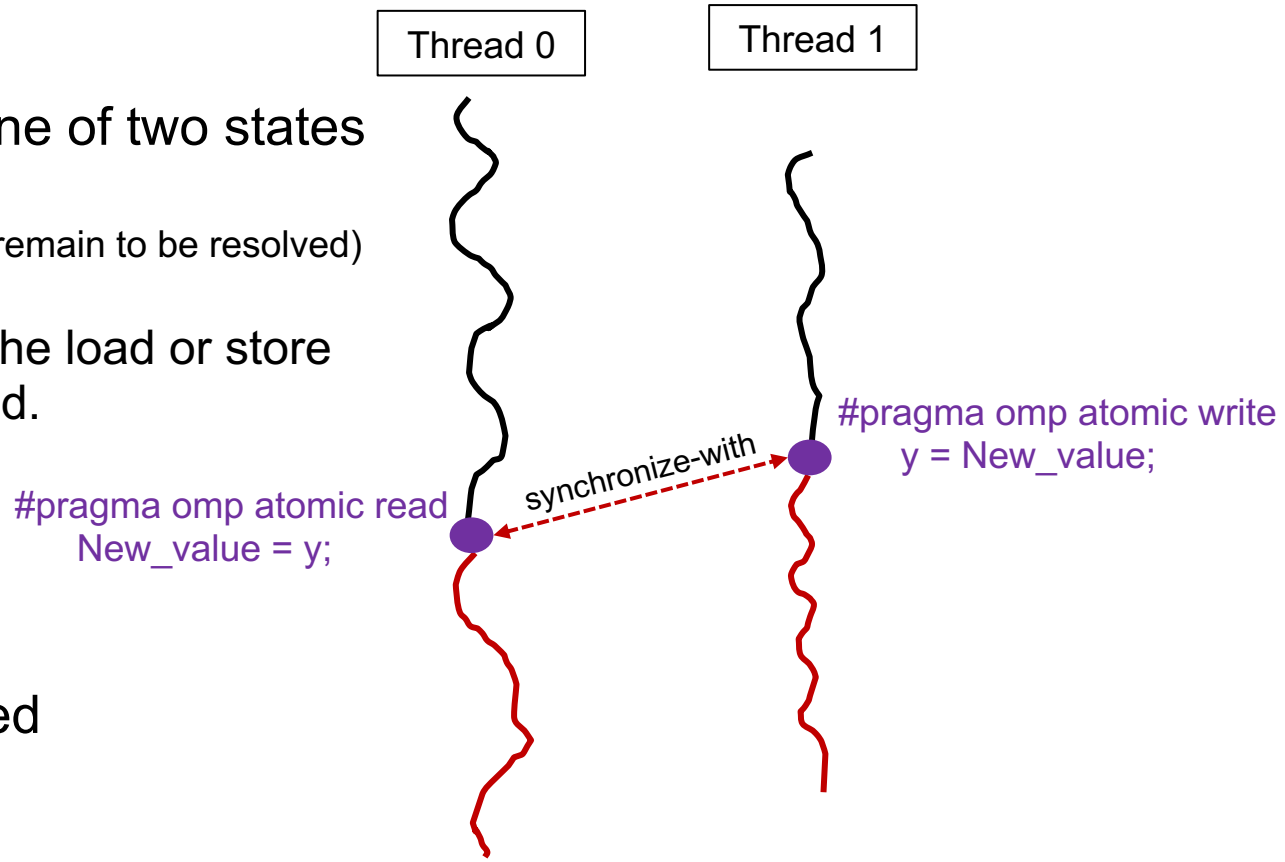
- Single thread execution:
  - Program order ... Loads and stores appear to occur in the order defined by the program's semantics. If you can't observe it, however, compilers can reorder instructions to maximize performance.
- Multithreaded execution … concurrency in action
  - The compiler doesn't understand instruction-ordering across threads … loads/stores to shared memory across threads can expose ambiguous orders of loads and stores
  - Instructions between threads are unordered except when specific ordering constraints are imposed, i.e., **synchronization**.
  - Synchronization lets us force that some instructions **happens-before** other instructions
- Two parts to synchronization:
  - A **synchronize-with** relationship exists at statements in 2 or more threads at which memory order constraints can be established.
  - **Memory order**: defines the view of loads/stores on either side of a synchronized-with operations.



Memory orders defined at the synchronize-with statements define happens-before relationships between Loads/stores in the black/red sections of threads 0 and 1.

Atomic Operations and Synchronized-with

- An atomic operation can only be observed in one of two states
  - The operation has not happened yet
  - The operation has happened and is complete (no side-effects remain to be resolved)
- For example, on an atomic load or store operation, the load or store has happened and is complete, or it has not occurred.



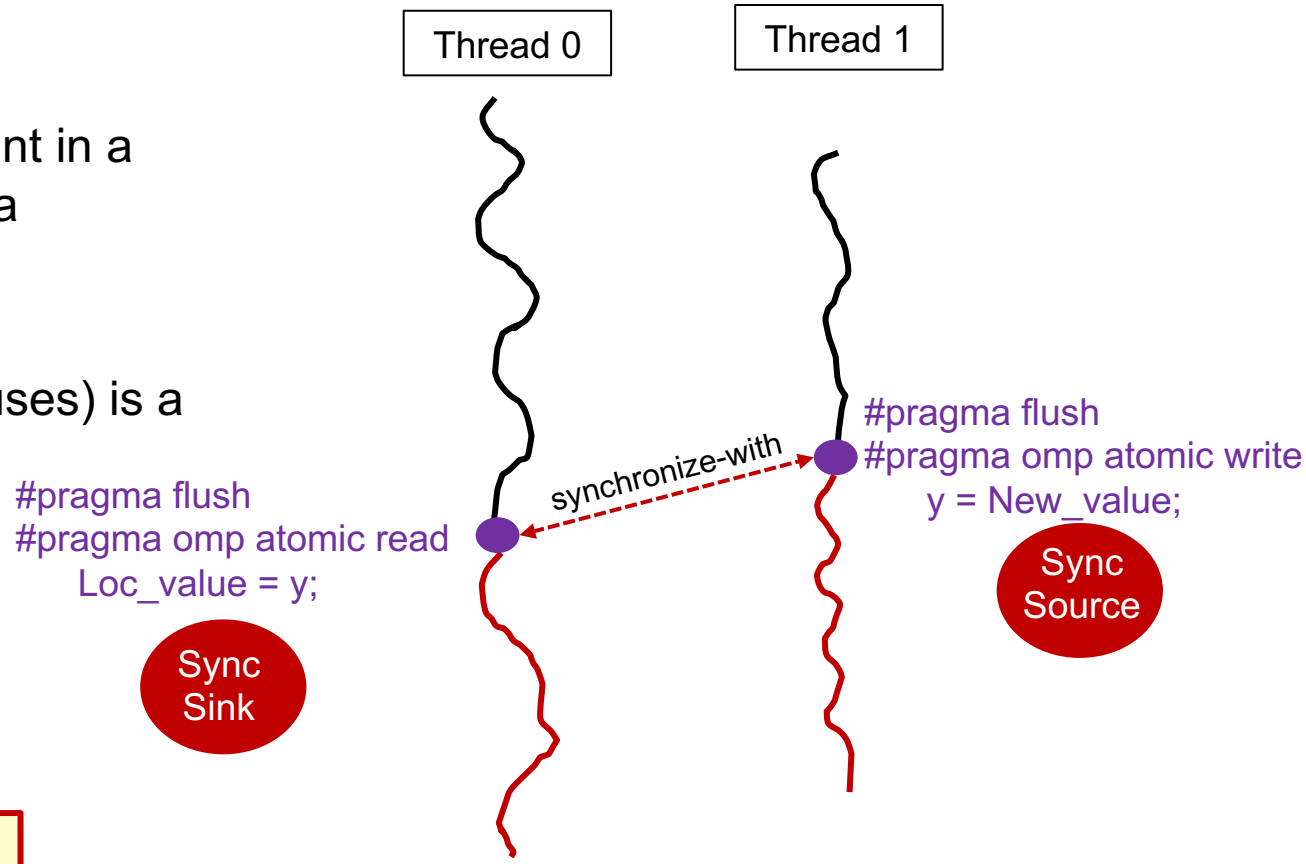
- A **synchronized-with** relationship is established between a pair of atomic operations.
- The variables involved are visible to the programmer (such as with atomic constructs) or the variables are internal to a high level synchronization construct (barrier, critical, locks, etc).

Memory orders

- Memory orders establish which loads and stores can be moved around synchronized-with relations.
- The key construct is **flush**. … flush defines a point in a program at which a thread is guaranteed to see a consistent view of memory.
- The default case for flush (i.e., no additional clauses) is a **strong flush**:
  - Previous read/writes by this thread have completed and are visible to other threads
  - No subsequent read/writes by this thread have occurred

A strong flush on its own does NOT define a synchronization point. The flush only addresses memory orders.

To synchronize threads, you need a synchronized-with relation which in this case, comes from an atomic write paired with an atomic read



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Black operations on Thread 1 happen-before Red operations on thread 0.

Memory orders

- Memory orders establish which loads and stores can be moved around synchronized-with relations.
- The strong flush by itself is expensive as it impacts all the shared variables visible to a thread.
- There are more focused forms of memory order
  The 2 most fundamental memory orders are:

read-acquire

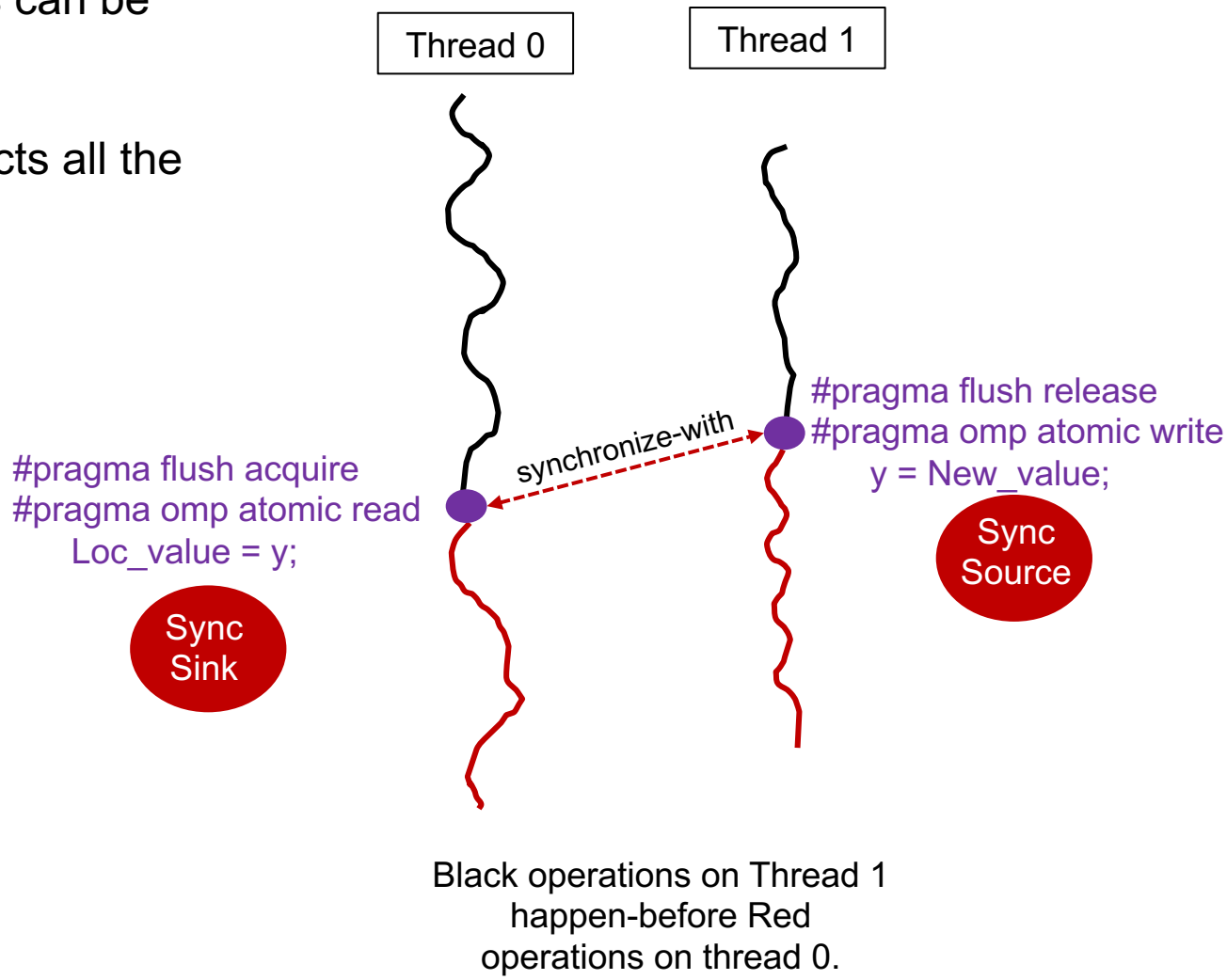
all memory operations stay below the line

– Acquire: Reads/writes that follow the read-with-acquire cannot happen-before the read-with-acquire operation.

all memory operations stay above the line

write-release

– Release: Reads/Writes prior to the write-with-release must happen-before the write-with-release.



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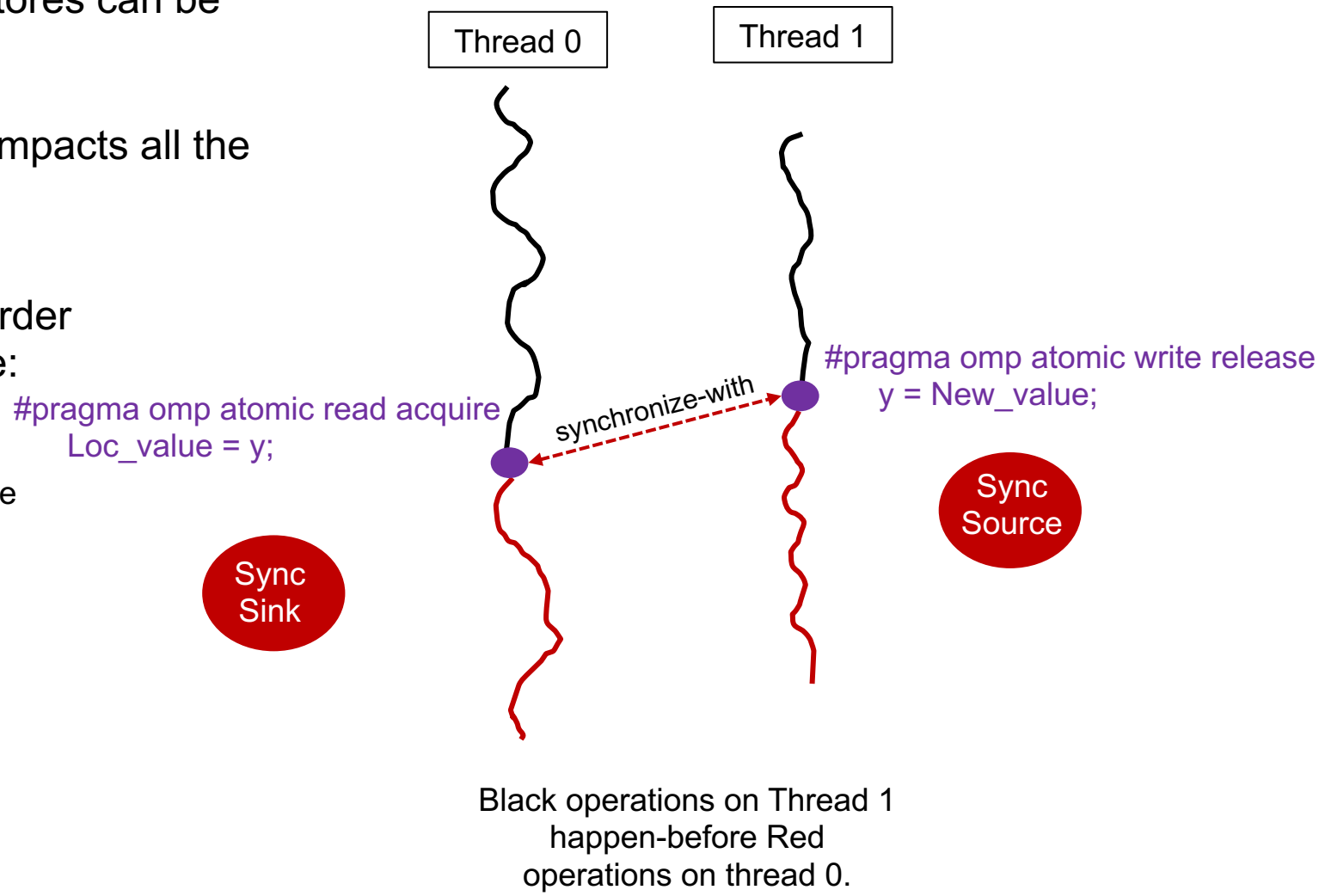


Black operations on Thread 1 happen-before Red operations on thread 0.

We can combine the flush and the atomic constructs

producer/consumer program correctly synchronized

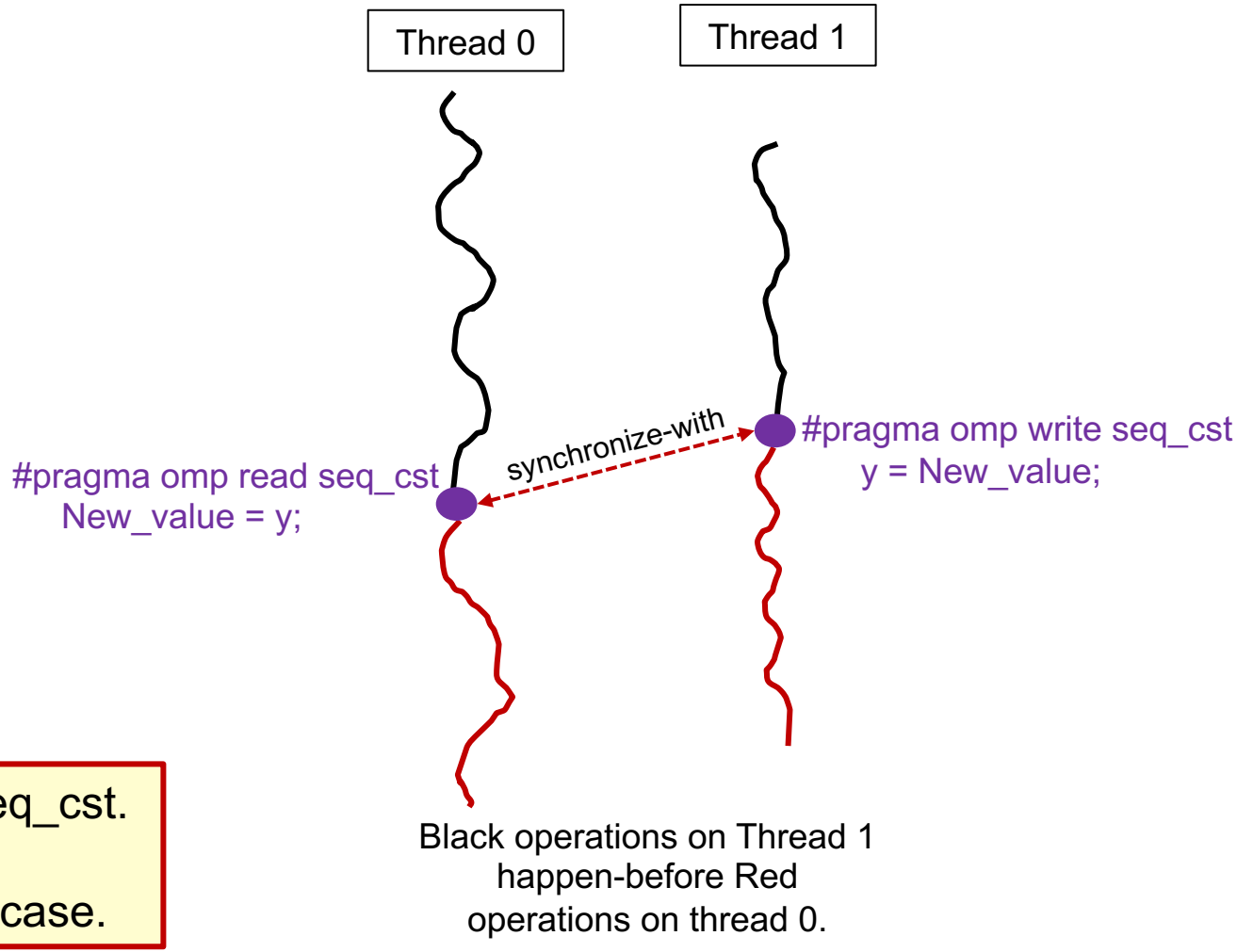
```
#include <stdio.h>
#include <omp.h>
#define COUNT 1000000
int main()
{
  int answer = 0, flag= 0,err=0;
  #pragma omp parallel shared(flag,answer) num_threads(2)
  {
    int id = omp_get_thread_num();
    if (id == 0) {
       answer = 42;
       #pragma omp write release
           flag = 1;
    }
    else if (id == 1){
       int fetch = 0;
       while (fetch == 0)  {
         #pragma omp atomic read acquire
           fetch = flag;
       }
       if(answer!=42) err++;
    }
  }
  return 0;
}
```

Other Memory orders in OpenMP

- Other OpenMP memory orders

  - **acq_rel**: Applies acquire and release memory order constraints at a single point in a program's execution.

  - **seq_cst**: sequential consistency. All data accessible to a thread are written to memory, subsequent writes are set to load from memory (akin to the strong flush)



The most important memory order to use is seq_cst.

It can be more expensive, but it is the safest case.

Keep it simple … let OpenMP take care of Flushes for you

- A flush operation is implied by OpenMP constructs …
  - at entry/exit of parallel regions
  - at implicit and explicit barriers
  - at entry/exit of critical regions

This has not been a detailed discussion of the full OpenMP memory model. The goal was to explain how memory models work and to understand the subset of features people commonly use.

- OpenMP programs that:
  - Do not use non-sequentially consistent atomic constructs;
  - Do not rely on the accuracy of a false result from omp_test_lock and omp_test_nest_lock; and
  - Correctly avoid data races

… behave as though operations on shared variables were simply interleaved in an order consistent with the order in which they are performed by each thread. The relaxed consistency model is invisible for such programs, and any explicit flushes in such programs are redundant.

WARNING:
If you find yourself wanting to write code with explicit flushes, stop and get help. It is very difficult to manage flushes on your own. Even experts often get them wrong.

This is why we defined OpenMP constructs to automatically apply flushes most places where you really need them.

One more Synchronization construct to cover: Locks

- A Lock provides mutual exclusion (just like the critical construct) but through lock variables and functions. Locks give you additional flexibility in how mutual exclusion fits in with your code.
- You create a lock variable:

```
omp_lock_t    my_lock;
```

- Initialize the lock:

```
omp_init_lock( my_lock);
```

- Set the lock … if the lock is not set already, you hold the lock. If it is set already, you wait until its unset:

```
omp_set_lock( my_lock);
```

Lock set and unset imply a strong flush

- When you are done … unset the lock so others can use it:

```
omp_unset_lock( my_lock);
```

Note: a thread always accesses the most recent copy of the lock, so you don't need to use a flush on the lock variable.

- When all threads are done … free resources used by the lock:

```
omp_destroy_lock( my_lock);
```

- Test if the lock is set. If it isn't set, the calling thread sets the lock. Otherwise, return false so it can do useful work while waiting.

```
while (!omp_test_lock(my_lock){
        // the lock is held by another thread
        // do something useful then try again
}
// you now have set the lock
```

Synchronization: Locks Example

- Count odds and evens in an input array(x) of N random values.

```
int i, ix, even_count = 0, odd_count = 0;
omp_lock_t odd_lck,   even_lck;
omp_init_lock(&odd_lck);
omp_init_lock(&even_lck);

#pragma omp parallel for private(ix) shared(even_count, odd_count)
 for(i=0; i<N; i++){
    ix = (int) x[i];  //truncate to int

    if(((int) x[i])%2 == 0) {
        omp_set_lock(&even_lck);
          even_count++;
        omp_unset_lock(&even_lck);
    }
    else{
        omp_set_lock(&odd_lck);
          odd_count++;
        omp_unset_lock(&odd_lck);
    }
 }
 omp_destroy_lock(&odd_lck);
 omp_destroy_lock(&even_lck);
}
```

One lock per case … even and odd

Enforce mutual exclusion updates, but in parallel for each case.

Free-up storage when done.

Outline

- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- Memory Model
- OpenMP stuff we didn't cover
- Recap

The OpenMP Common Core: Most OpenMP programs only use these 21 items

We covered most of the common core

OpenMP pragma, function, or clause	Concepts
#pragma omp parallel	Parallel region, teams of threads, structured block, interleaved execution across threads.
void omp_set_thread_num() int omp_get_thread_num() int omp_get_num_threads()	Default number of threads and internal control variables. SPMD pattern: Create threads with a parallel region and split up the work using the number of threads and the thread ID.
double omp_get_wtime()	Speedup and Amdahl's law. False sharing and other performance issues.
setenv OMP_NUM_THREADS N	Setting the internal control variable for the default number of threads with an environment variable
#pragma omp barrier #pragma omp critical	Synchronization and race conditions. Revisit interleaved execution.
#pragma omp for #pragma omp parallel for	Worksharing, parallel loops, loop carried dependencies.
reduction(op:list)	Reductions of values across a team of threads.
schedule (static [,chunk]) schedule(dynamic [,chunk])	Loop schedules, loop overheads, and load balance.
shared(list), private(list), firstprivate(list)	Data environment.
default(none)	Force explicit definition of each variable's storage attribute
nowait	Disabling implied barriers on workshare constructs, the high cost of barriers, and the flush concept (but not the flush directive).
#pragma omp single	Workshare with a single thread.
#pragma omp task #pragma omp taskwait	Tasks including the data environment for tasks.

We skipped tasking since you'll do it with TBB (which does tasking better than OpenMP)

… But more importantly, we covered the most of the concepts you need to understand parallel computing

- Parallelism vs concurrency … and how it maps onto GPUs and CPUs
- How we talk about performance: Speedup and Amdahl's law
- SPMD and Loop level parallelism design patterns
- Load Balancing
- False sharing, race conditions, and other challenges of shared address spaces
- Memory models and the challenges of working with them
- Synchronization: mutual exclusion, barriers, and atomic operations with flush

Parallel Fibonacci with OpenMP tasks

```
int fib (int n)
{   int x,y;
   if (n < 2) return n;

#pragma omp task shared(x)
   x = fib(n-1);
#pragma omp task shared(y)
   y = fib (n-2);
#pragma omp taskwait
   return (x+y);
}

Int main()
{  int NW = 5000;
   #pragma omp parallel
   {
      #pragma omp single
            fib(NW);
   }
}
```

- Binary tree of tasks
- Traversed using a recursive function
- A task cannot complete until all tasks below it in the tree are complete (enforced with taskwait)
- `x,y` are local, and so by default they are private to current task
  - must be shared on child tasks so they don't create their own firstprivate copies at this level!

GPU programming: Vector addition with CUDA

Avoid CUDA … it is proprietary and will lock you in to NVIDIA

```
// Compute sum of length-N vectors: C = A + B
void __global__
vecAdd (float* a, float* b, float* c, int N) {
    int i = blockIdx.x * blockDim.x + threadIdx.x;
    if (i < N) c[i] = a[i] + b[i];
}

int main () {
    int N = ... ;
    float *a, *b, *c;
    cudaMalloc (&a,  sizeof(float) * N);
  // ... allocate other arrays (b and c), fill with data

  // Use thread blocks with 256 threads each
    vecAdd <<< (N+255)/256, 256 >>> (a, b, c, N);
}
```

CUDA kernel as function

Unified shared memory … allocate on host, visible on device too

Enqueue the kernel to execute on the Grid

GPU programming: Vector addition with SYCL

```
// Compute sum of length-N vectors: C = A + B
#include <CL/sycl.hpp>

int main () {
    int N = ... ;
    float *a, *b, *c;
    sycl::queue q;
    *a = (float *)sycl::malloc_shared(N * sizeof(float), q);
  // ... allocate other arrays (b and c), fill with data

        q.parallel_for(sycl::range<1>{N},
                [=](sycl::id<1> i) {
                  c[i] = a[i] + b[i];
                });
         q.wait();
}
```

Create a queue for SYCL commands

Unified shared memory … allocate on host, visible on device too

Kernel as a C++ Lambda function

[=] means capture external variables by value.

Vector addition with OpenMP

- Let's add two vectors together …. C = A + B

```
int main(){
  float *a, *b, *c;  int n = 10000;
  // allocate and fill a and b

  #pragma omp target map(to:a(0:n), b(0:n)) map(tofrom:c(0:n))
  #pragma omp loop
   for (i=0; i<n; i++)
     c[i] = a[i] + b[i];

}
```

This code is portable … it works with or without Unified Shared Memory

Outline

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OpenMP Organizations

- OpenMP Architecture Review Board (ARB) URL, the “owner” of the OpenMP specification:

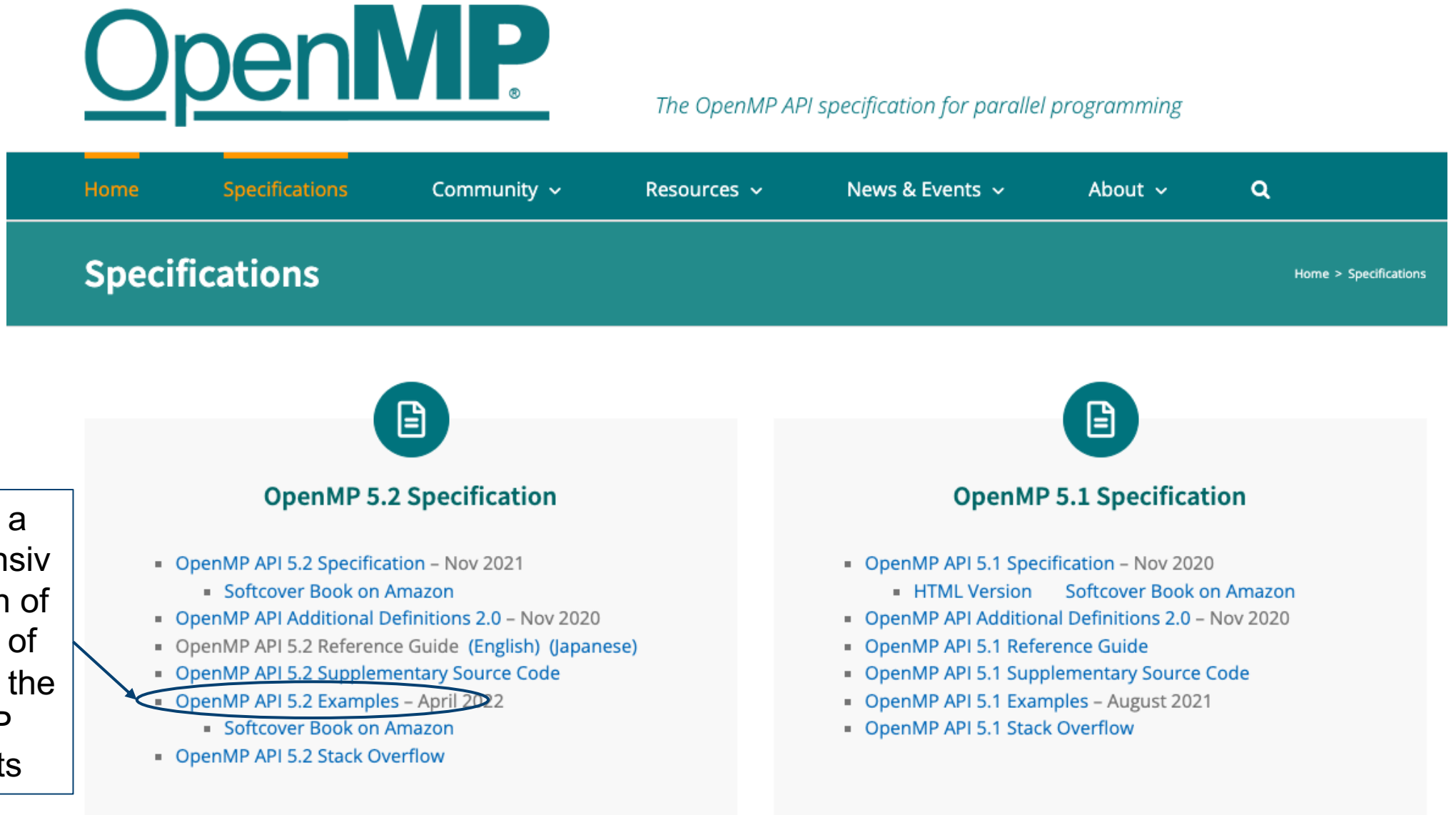
  www.openmp.org

Get involved, get your organization to join the ARB.

Help define the future of OpenMP

Resources

- www.openmp.org has a wealth of helpful resources



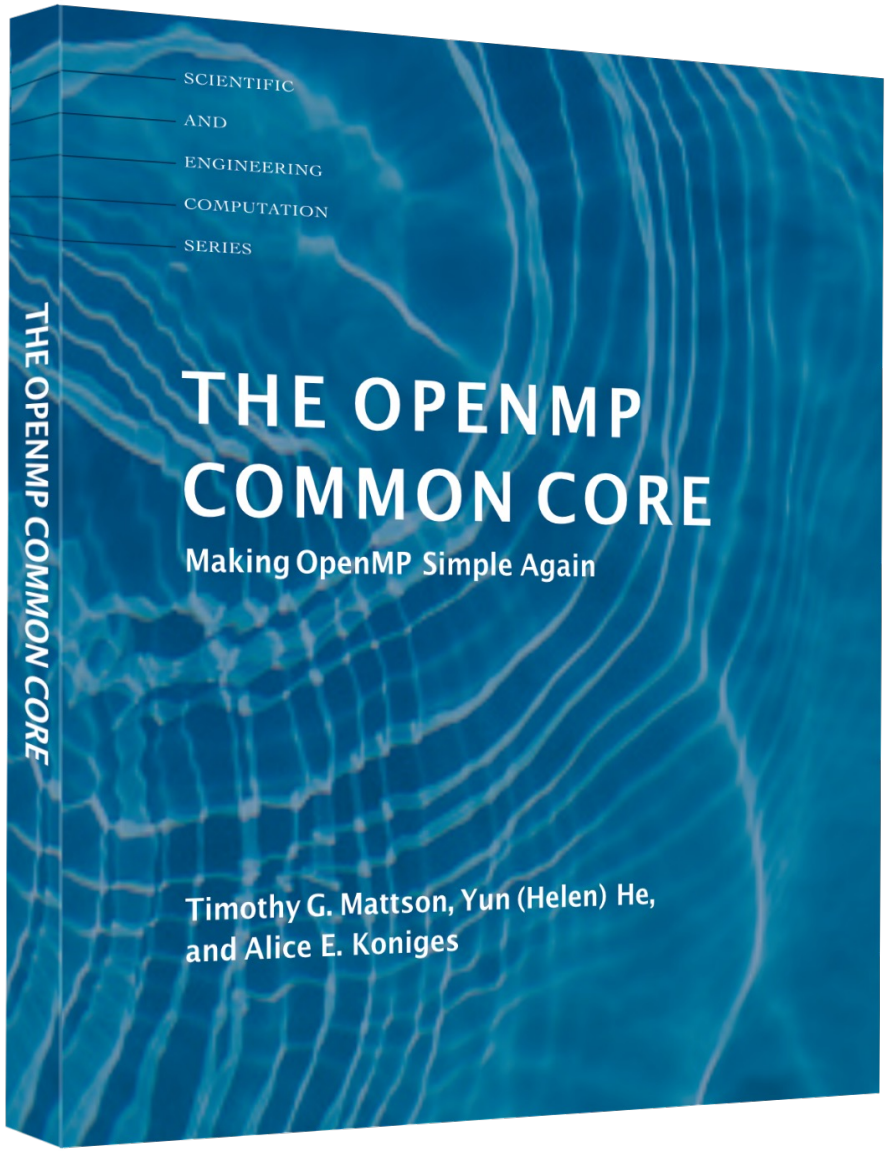
Including a comprehensive collection of examples of code using the OpenMP constructs

To learn OpenMP:

- An exciting new book that Covers the Common Core of OpenMP plus a few key features beyond the common core that people frequently use

- It's geared towards people learning OpenMP, but as one commentator put it … **everyone at any skill level should read the memory model chapters**.

- Available from MIT Press



www.ompcore.com for code samples and the Fortran supplement

Books about OpenMP

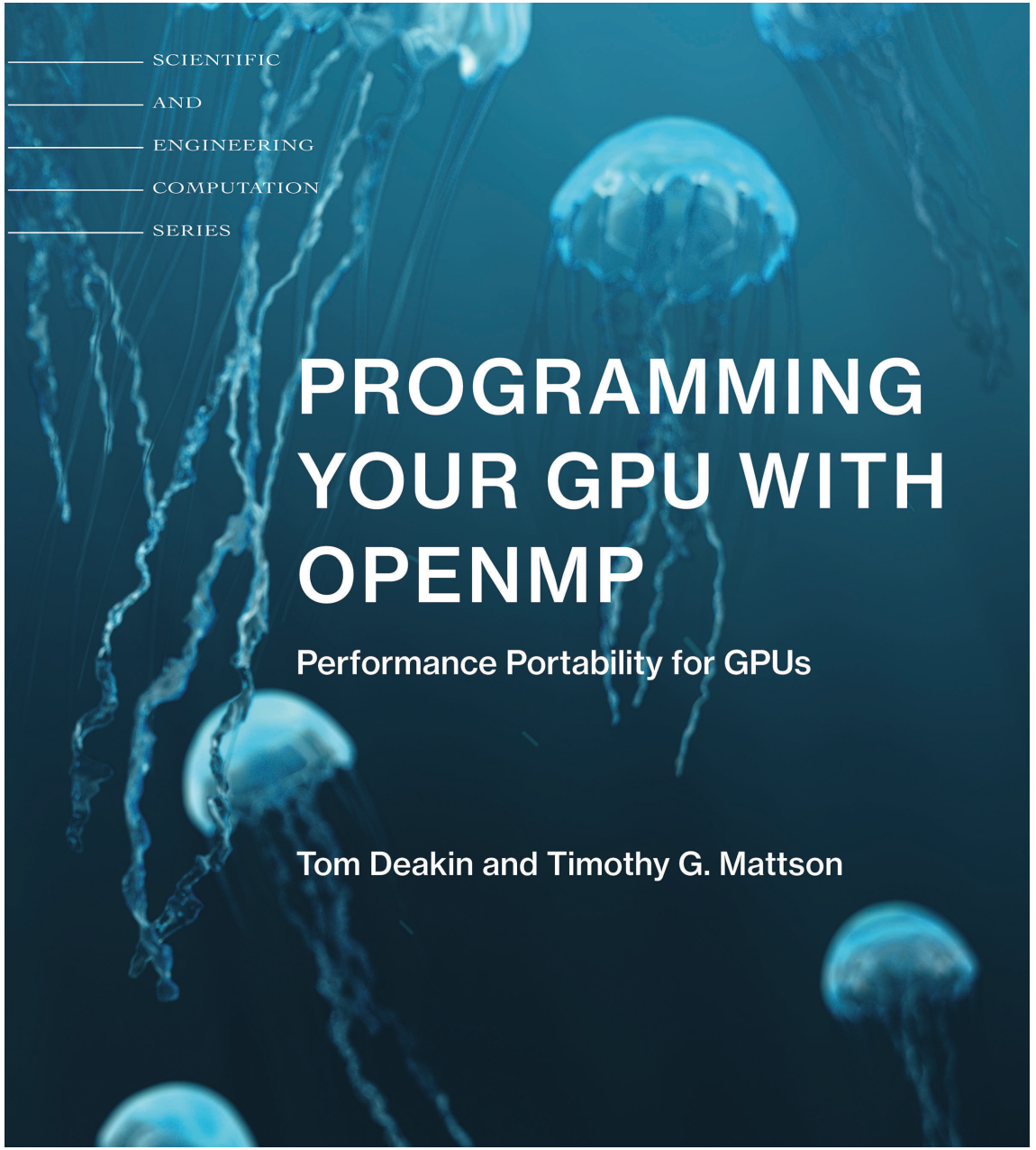
A great book that covers OpenMP features beyond OpenMP 2.5

Books about OpenMP

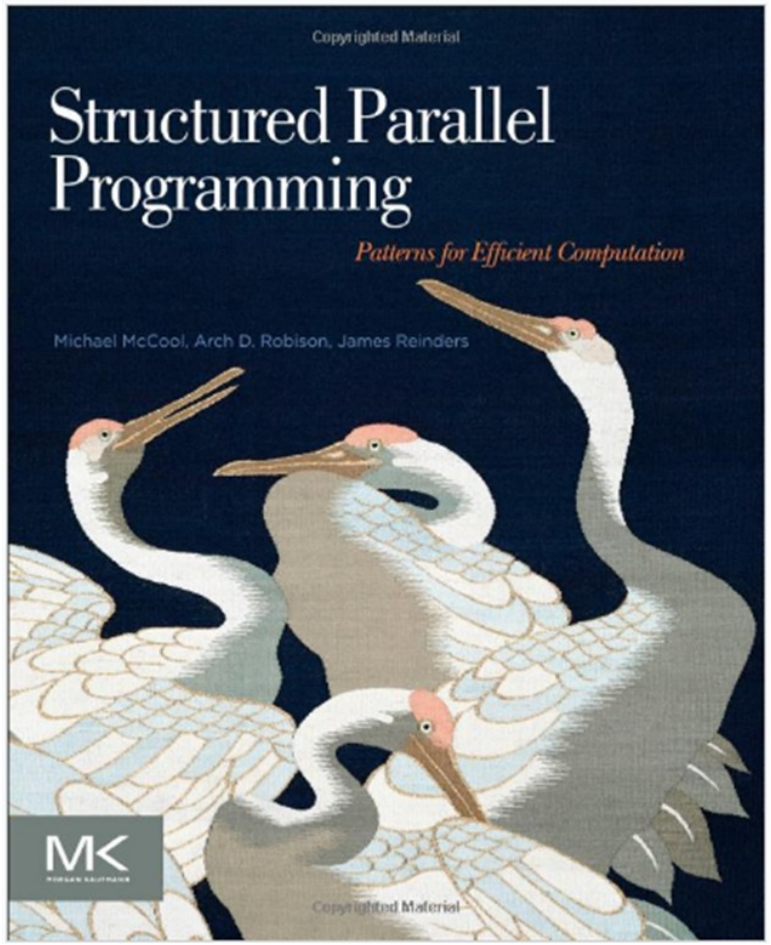
The latest book on OpenMP …

Came out in early November 2023.

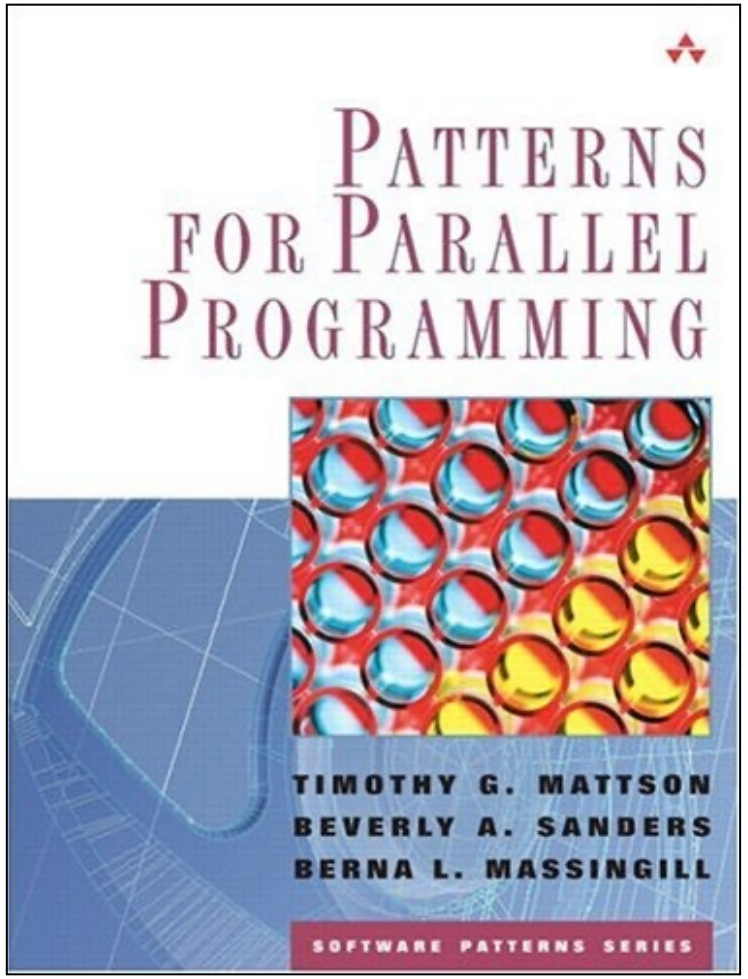
A book about how to use OpenMP to program a GPU.



Background references

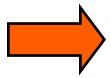


A great book that explores key patterns with Cilk, TBB, OpenCL, and OpenMP (by McCool, Robison, and Reinders)



- A book about how to "think parallel" with examples in OpenMP, MPI and java

Backup content



- Extra exercises
- Irregular parallelism and OpenMP tasks
- Worksharing Revisited
- Synchronization Revisited: Additional options for Mutual exclusion

Additional exercises for consolidation

- We provide three exercises you can use to solidify your understanding of OpenMP.
  1. Optimizing the Mandelbrot-area program.
  2. Building a histogram in parallel: This exercise explores different ways to synchronize code and how they impact performance. Given the importance of synchronization in multithreaded programming, this is an important skill to refine.
  3. Traversing linked lists: OpenMP added tasks to solve what we call irregular parallelism (i.e., they do not map onto basic for-loops). Parallelizing the traversal of linked lists with using tasks requires a lot of creativity. There are several ways to do this each with different impacts on performance.

- In some cases, the exercises content we presented, but didn't include in prior exercises. Hence, expect to need to review the lecture slides to figure out some key details.

Exercise: Mandelbrot set area

- The supplied program (mandel.c) computes the area of a Mandelbrot set.
- The program has been parallelized with OpenMP, but we were lazy and didn't do it right.
- Find and fix the errors.
- Once you have a working version, try to optimize the program.

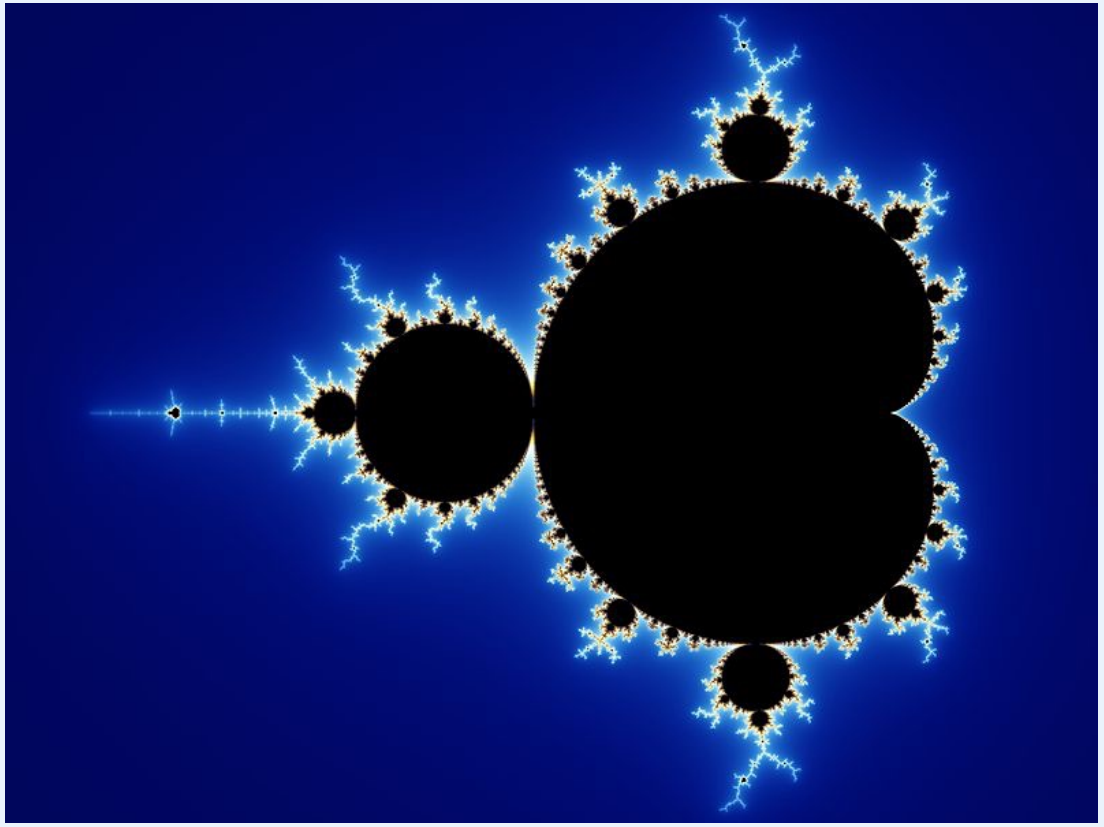


Image Source: Created by Wolfgang Beyer with the program Ultra Fractal 3. - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=321973

The Mandelbrot set … The points, c, for which the following iterative map converges

$$z_{n+1} = z_n^2 + c$$

With z_n and c as complex numbers and $z_0 = 0$.

```
#pragma omp parallel
#pragma omp for
#pragma omp parallel for
#pragma omp critical
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
```

```
#pragma omp parallel private (list)
#pragma omp parallel shared (list)
#pragma omp parallel firstprivate (list)
#pragma omp parallel default(none)
#pragma omp for reduction(op:list)
```

This exercise come from Mark Bull of EPCC (at University of Edinburgh)

Exercise: different options for synchronization

- In the file **hist.c**, we provide a program that generates a large array of random numbers and then generates a histogram of those values.
- This is a ”quick and informal” way to test a random number generator … if all goes well the bins of the histogram should be the same size.
- Parallelize the filling of the histogram You must assure that your program is race free and gets the same result as the sequential program.
- Using everything we've covered today, manage updates to shared data in multiple ways. Try to minimize the time to generate the histogram.
- Time ONLY the assignment to the histogram. Can you beat the sequential time?

```
#define     num_trials    1000000 // number of x values
#define     num_buckets   50      // number of buckets in histogram
static long xlow        = 0.0;     // low end of x range
static long xhi         = 100.0;   // High end of x range

int main (){
   double x[num_trials];     // array used to assign counters in the historgram
   long   hist[num_buckets]; // the histogram
   double bucket_width;      // the width of each bucket in the histogram
   double time;

   seed(xlow, xhi);  // seed the random number generator over range of x
   bucket_width = (xhi-xlow)/(double)num_buckets;

   // fill the array. << code not shown >>

  // initialize the histogram << code not shown >>

  // Assign x values to the right histogram bucket
   time = omp_get_wtime();
   for(int i=0;i<num_trials;i++){

      long ival = (long) (x[i] - xlow)/bucket_width;

      hist[ival]++;

   }

  time = omp_get_wtime() - time;

   // compute statistics and output results << code not shown >>
   return 0;
}
```

Only focus on this part of the program

Exercise: Traversing linked lists

- Consider the program linked.c
  - Traverses a linked list computing a sequence of Fibonacci numbers at each node.
- Parallelize this program selecting from the following list of constructs:

  #pragma omp parallel

  #pragma omp for

  #pragma omp parallel for

  #pragma omp for reduction(op:list)

  #pragma omp critical

  int omp_get_num_threads();

  int omp_get_thread_num();

  double omp_get_wtime();

  schedule(static[,chunk]) or schedule(dynamic[,chunk])

  private(), firstprivate(), default(none)

```
p = listhead ;
while (p) {
  process(p);
  p=p->next;
}
```

  - Hint: Just worry about the while loop that is timed inside main(). Don't make any changes to the "process functions"

Backup content

- Extra exercises
- Irregular parallelism and OpenMP tasks
- Worksharing Revisited
- Synchronization Revisited: Additional options for Mutual exclusion

Irregular Parallelism

- Let's call a problem "irregular" when one or both of the following hold:
  - Data Structures are sparse or involve indirect memory references
  - Control structures are not basic for-loops

- Example: Traversing Linked lists:

```
p = listhead ;
while (p) {
  process(p);
  p=p->next;
}
```

- Using what we've learned so far, traversing a linked list in parallel using OpenMP is difficult.

Exercise: Traversing linked lists

- Consider the program linked.c
  - Traverses a linked list computing a sequence of Fibonacci numbers at each node.
- Parallelize this program selecting from the following list of constructs:

```
#pragma omp parallel
#pragma omp for
#pragma omp parallel for
#pragma omp for reduction(op:list)
#pragma omp critical
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
schedule(static[,chunk]) or schedule(dynamic[,chunk])
private(), firstprivate(), default(none)
```

- Hint: Just worry about the while loop that is timed inside main(). You don't need to make any changes to the "list functions"

Linked Lists with OpenMP (without tasks)

- See the file solutions/linked_notasks.c

```
while (p != NULL) {
     p = p->next;
      count++;
}
struct node *parr = (struct node*) malloc(count*sizeof(struct node));
p = head;
for(i=0; i<count; i++) {
      parr[i] = p;
      p = p->next;
   }
#pragma omp parallel
{
    #pragma omp for schedule(static,1)
    for(i=0; i<count; i++)
       processwork(parr[i]);
}
```

Count number of items in the linked list

Copy pointer to each node into an array

Process nodes in parallel with a for loop

Number of threads	Schedule	
	Default	Static,1
1	48 seconds	45 seconds
2	39 seconds	28 seconds

Results on an Intel dual core 1.83 GHz CPU, Intel IA-32 compiler 10.1 build 2

Linked Lists with OpenMP (without tasks)

- See the file solutions/linked_notasks.c

```
while (p != NULL) {
     p = p->next;
      count++;
}
struct node *parr = (struct node*) malloc(count*sizeof(struct node));
p = head;
for(i=0; i<count; i++) {
      parr[i] = p;
      p = p->next;
   }
#pragma omp parallel
{
    #pragma omp for schedule(static,1)
    for(i=0; i<count; i++)
       processwork(parr[i]);
}
```

Count number of items in the linked list

Copy pointer to each node into an array

Process nodes in parallel with a for loop

With so much code to add and three passes through the data, this is really ugly.

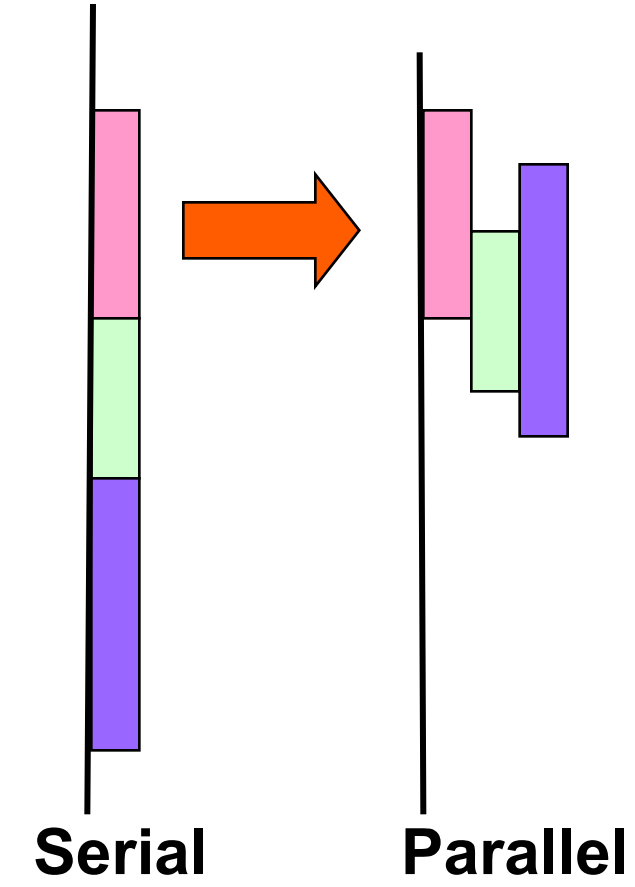
There has got to be a better way to do this

Number of threads	Schedule	
	Default	Static,1
1	48 seconds	45 seconds
2	39 seconds	28 seconds

Results on an Intel dual core 1.83 GHz CPU, Intel IA-32 compiler 10.1 build 2

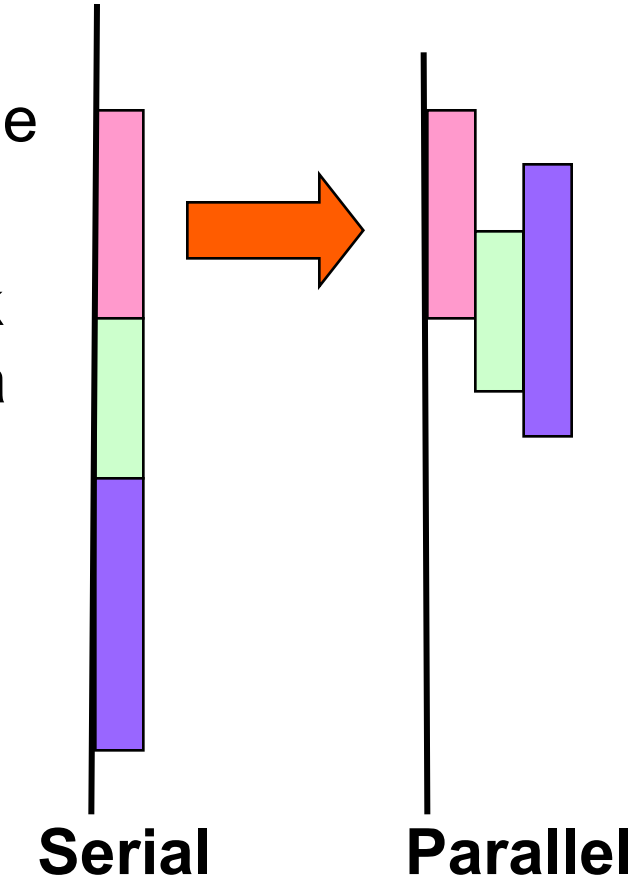
What are Tasks?

- Tasks are independent units of work
- Tasks are composed of:
  - code to execute
  - data to compute with
- Threads are assigned to perform the work of each task.
  - The thread that encounters the task construct may execute the task immediately.
  - The threads may defer execution until later



What are Tasks?

- The task construct includes a structured block of code
- Inside a parallel region, a thread encountering a task construct will package up the code block and its data for execution
- Tasks can be nested: i.e., a task may itself generate tasks.



A common Pattern is to have one thread create the tasks while the other threads wait at a barrier and execute the tasks

Single Worksharing Construct

- The **single** construct denotes a block of code that is executed by only one thread (not necessarily the primary* thread).
- A barrier is implied at the end of the single block (can remove the barrier with a *nowait* clause).

```
#pragma omp parallel
{
        do_many_things();
    #pragma omp single
        {   exchange_boundaries();  }
        do_many_other_things();
}
```

*This used to be called the “master thread”. The term “master” has been deprecated in OpenMP 5.1 and replaced with the term “primary”.

Task Directive

`#pragma omp task` *[clauses]*

structured-block

```
#pragma omp parallel
{
  #pragma omp single
   {
     #pragma omp task
        fred();
     #pragma omp task
        daisy();
     #pragma omp task
        billy();
   }
}
```

Create some threads

One Thread packages tasks

Tasks executed by some thread in some order

All tasks complete before this barrier is released

Exercise: Simple tasks

- Write a program using tasks that will “randomly” generate one of two strings:
  - “I think “ “race” “car” “s are fun”
  - “I think “ “car” “race” “s are fun”

- Hint: use tasks to print the indeterminate part of the output (i.e. the “race” or “car” parts).

- This is called a “Race Condition”. It occurs when the result of a program depends on how the OS schedules the threads.

- NOTE: A “data race” is when threads “race to update a shared variable”. They produce race conditions. Programs containing data races are undefined (in OpenMP but also ANSI standards C++’11 and beyond).

```
#pragma omp parallel
#pragma omp task
#pragma omp single
```

This exercise comes from Ruud van der Pas of Oracle

Racey Cars: Solution

```
#include <stdio.h>
#include <omp.h>
int main()
{  printf("I think");
   #pragma omp parallel
   {
      #pragma omp single
      {
         #pragma omp task
            printf(" car");
         #pragma omp task
            printf(" race");
      }
   }
   printf("s");
   printf(" are fun!\n");
}
```

Data Scoping with Tasks

- Variables can be shared, private or firstprivate with respect to task

- These concepts are a little bit different compared with threads:
  - If a variable is shared on a task construct, the references to it inside the construct are to the storage with that name at the point where the task was encountered
  - If a variable is private on a task construct, the references to it inside the construct are to new uninitialized storage that is created when the task is executed
  - If a variable is firstprivate on a construct, the references to it inside the construct are to new storage that is created and initialized with the value of the existing storage of that name when the task is encountered

Data Scoping Defaults

- The behavior you want for tasks is usually firstprivate, because the task may not be executed until later (and variables may have gone out of scope)
  - Variables that are private when the task construct is encountered are firstprivate by default

- Variables that are shared in all constructs starting from the innermost enclosing parallel construct are shared by default

```
#pragma omp parallel shared(A) private(B)
{
    ...
#pragma omp task
    {
        int C;
        compute(A, B, C);
    }
}
```

A is shared
B is firstprivate
C is private

Exercise: Traversing linked lists

- Consider the program linked.c
  - Traverses a linked list computing a sequence of Fibonacci numbers at each node.
- Parallelize this program selecting from the following list of constructs:

```
#pragma omp parallel
#pragma omp single
#pragma omp task
int omp_get_num_threads();
int omp_get_thread_num();
double omp_get_wtime();
private(), firstprivate()
```

- Hint: Just worry about the contents of main(). You don't need to make any changes to the "list functions"

Parallel Linked List Traversal

```
#pragma omp parallel
{
  #pragma omp single
   {
    p = listhead ;
    while (p) {
       #pragma omp task firstprivate(p)
              {
                process (p);
              }
       p=next (p) ;
     }
   }
}
```

Only one thread packages tasks

makes a copy of `p` when the task is packaged

When/Where are Tasks Complete?

- At thread barriers (explicit or implicit)
  - all tasks generated inside a region must complete at the next barrier encountered by the threads in that region. Common examples:
    - **Tasks generated inside a single construct**: all tasks complete before exiting the barrier on the single.
    - **Tasks generated inside a parallel region**: all tasks complete before exiting the barrier at the end of the parallel region.

- At taskwait directive
  - i.e. Wait until all tasks defined in the current task have completed.

```
#pragma omp taskwait
```

  - Note: applies only to tasks generated in the current task, not to “descendants” .

Example

```
#pragma omp parallel
{
  #pragma omp single
   {
     #pragma omp task
        fred();
     #pragma omp task
        daisy();
     #pragma omp taskwait
     #pragma omp task
        billy();
   }
}
```

`fred()` and `daisy()` must complete before `billy()` starts, but this does not include tasks created inside **fred()** and **daisy()**

`All tasks` including those created inside **fred()** and **daisy()** must complete before exiting this barrier

Example

```
#pragma omp parallel
{
  #pragma omp single nowait
   {
     #pragma omp task
        fred();
     #pragma omp task
        daisy();
     #pragma omp taskwait
     #pragma omp task
        billy();
   }
}
```

The barrier at the end of the single is expensive and not needed since you get the barrier at the end of the parallel region. So use nowait to turn it off.

All tasks including those created inside **fred()** and **daisy()** must complete before exiting this barrier

Example: Fibonacci numbers

```
int fib (int n)
{
   int x,y;
   if (n < 2) return n;

   x = fib(n-1);
   y = fib (n-2);
   return (x+y);
}

int main()
{
   int NW = 5000;
   fib(NW);
}
```

- $F_n = F_{n-1} + F_{n-2}$
- Inefficient $O(2^n)$ recursive implementation!

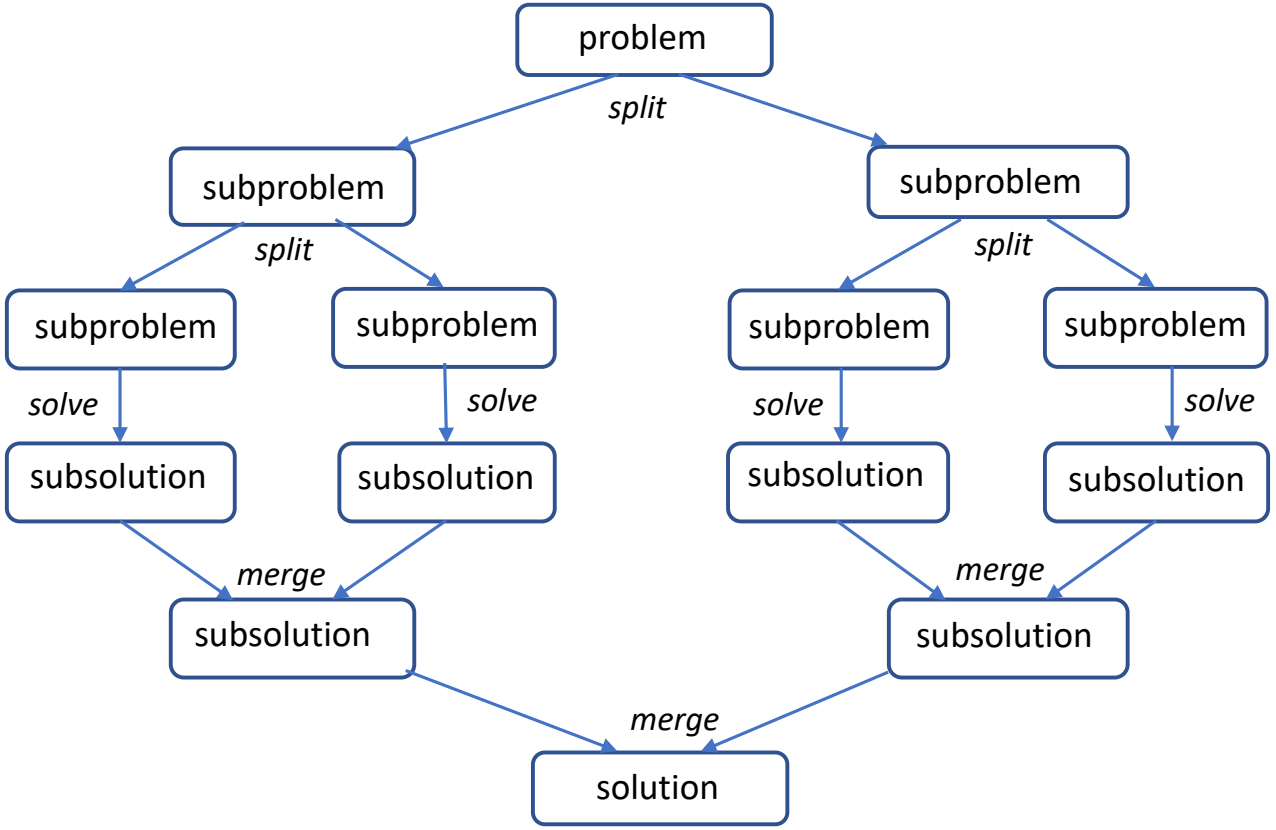
Parallel Fibonacci

```
int fib (int n)
{   int x,y;
   if (n < 2) return n;

#pragma omp task shared(x)
   x = fib(n-1);
#pragma omp task shared(y)
   y = fib (n-2);
#pragma omp taskwait
   return (x+y);
}

Int main()
{  int NW = 5000;
   #pragma omp parallel
   {
      #pragma omp single
           fib(NW);
   }
}
```

- Binary tree of tasks
- Traversed using a recursive function
- A task cannot complete until all tasks below it in the tree are complete (enforced with taskwait)
- `x,y` are local, and so by default they are private to current task
  - must be shared on child tasks so they don't create their own firstprivate copies at this level!

Divide and Conquer

- Split the problem into smaller sub-problems; continue until the sub-problems can be solved directly



- 3 Options for parallelism:
  - Do work as you split into sub-problems
  - Do work only at the leaves
  - Do work as you recombine

Exercise: PI with tasks

- Go back to the original pi.c program
  - Parallelize this program using OpenMP tasks

```
#pragma omp parallel
#pragma omp task
#pragma omp taskwait
#pragma omp single
double omp_get_wtime()
int omp_get_thread_num();
int omp_get_num_threads();
```

- Hint: first create a recursive pi program and verify that it works. **Think about the computation you want to do at the leaves. If you go all the way down to one iteration per leaf-node, won't you just swamp the system with tasks?**

Program: OpenMP tasks

```
include <omp.h>
static long num_steps = 100000000;
#define MIN_BLK  10000000
double pi_comp(int Nstart,int Nfinish,double step)
{   int i,iblk;
    double x, sum = 0.0,sum1, sum2;
    if (Nfinish-Nstart < MIN_BLK){
      for (i=Nstart;i< Nfinish; i++){
        x = (i+0.5)*step;
        sum = sum + 4.0/(1.0+x*x);
      }
    }
    else{
      iblk = Nfinish-Nstart;
      #pragma omp task shared(sum1)
          sum1 = pi_comp(Nstart,        Nfinish-iblk/2,step);
      #pragma omp task shared(sum2)
          sum2 = pi_comp(Nfinish-iblk/2, Nfinish,      step);
      #pragma omp taskwait
        sum = sum1 + sum2;
   }return sum;
}
```

```
int main ()
{
  int i;
  double step, pi, sum;
   step = 1.0/(double) num_steps;
   #pragma omp parallel
   {
      #pragma omp single
          sum =
              pi_comp(0,num_steps,step);
    }
     pi = step * sum;
}
```

Results*: Pi with tasks

threads	1st SPMD	SPMD critical	PI Loop	Pi tasks
1	1.86	1.87	1.91	1.87
2	1.03	1.00	1.02	1.00
3	1.08	0.68	0.80	0.76
4	0.97	0.53	0.68	0.52

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core™ i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

Using Tasks

- Don’t use tasks for things already well supported by OpenMP
  - e.g. standard do/for loops
  - the overhead of using tasks is greater

- Don’t expect miracles from the runtime
  - best results usually obtained where the user controls the number and granularity of tasks

Backup content

- Extra exercises
- Irregular parallelism and OpenMP tasks
- Worksharing Revisited
- Synchronization Revisited: Additional options for Mutual exclusion

The Loop Worksharing Constructs

- The loop worksharing construct splits up loop iterations among the threads in a team

```
#pragma omp parallel
{
#pragma omp for
        for (I=0;I<N;I++){
                NEAT_STUFF(I);
        }
}
```

The variable I is made “private” to each thread by default. You could do this explicitly with a “private(I)” clause

Loop construct name:

- C/C++: for
- Fortran: do

Loop Worksharing Constructs: The schedule clause

- The schedule clause affects how loop iterations are mapped onto threads
  - **schedule(static [,chunk])**
    - Deal-out blocks of iterations of size “chunk” to each thread.
  - **schedule(dynamic[,chunk])**
    - Each thread grabs “chunk” iterations off a queue until all iterations have been handled.
  - **schedule(guided[,chunk])**
    - Threads dynamically grab blocks of iterations. The size of the block starts large and shrinks down to size “chunk” as the calculation proceeds.
  - **schedule(runtime)**
    - Schedule and chunk size taken from the OMP_SCHEDULE environment variable (or the runtime library) … vary schedule without a recompile!
  - **Schedule(auto)**
    - Schedule is left up to the runtime to choose (does not have to be any of the above).

OpenMP 4.5 added modifiers monotonic, nonmontonic and simd.

Loop Worksharing Constructs: The schedule clause

Schedule Clause	When To Use
STATIC	Pre-determined and predictable by the programmer
DYNAMIC	Unpredictable, highly variable work per iteration
GUIDED	Special case of dynamic to reduce scheduling overhead
AUTO	When the runtime can “learn” from previous executions of the same loop

Least work at runtime : scheduling done at compile-time

Most work at runtime : complex scheduling logic used at run-time

Nested Loops

- For perfectly nested rectangular loops we can parallelize multiple loops in the nest with the collapse clause:

```
#pragma omp parallel for collapse(2)
for (int i=0; i<N; i++) {
  for (int j=0; j<M; j++) {
          .....
  }
}
```

Number of loops to be parallelized, counting from the outside

- Will form a single loop of length NxM and then parallelize that.
- Useful if N is O(no. of threads) so parallelizing the outer loop makes balancing the load difficult.

Sections Worksharing Construct

- The *Sections* worksharing construct gives a different structured block to each thread.

```
#pragma omp parallel
{
   #pragma omp sections
   {
   #pragma omp section
            x_calculation();
   #pragma omp section
             y_calculation();
   #pragma omp section
             z_calculation();
   }
}
```

By default, there is a barrier at the end of the “omp sections”. Use the “nowait” clause to turn off the barrier.

Array Sections with Reduce

```
#include <stdio.h>
#define N 100
void init(int n, float (*b)[N]);
int main(){
int i,j; float a[N], b[N][N]; init(N,b);
for(i=0; i<N; i++)  a[i]=0.0e0;

#pragma omp parallel for reduction(+:a[0:N]) private(j)
for(i=0; i<N; i++){
  for(j=0; j<N; j++){
       a[j] += b[i][j];
  }
}
printf(" a[0] a[N-1]: %f %f\n", a[0], a[N-1]);
return 0;
```

Works the same as any other reduce … a private array is formed for each thread, element wise combination across threads and then with original array at the end

Exercise

- Go back to your parallel mandel.c program.
- Using what we've learned in this block of slides can you improve the runtime?

Optimizing mandel.c

```
  wtime = omp_get_wtime();
#pragma omp parallel for collapse(2) schedule(runtime) firstprivate(eps) private(j,c)
  for (i=0; i<NPOINTS; i++) {
    for (j=0; j<NPOINTS; j++) {
      c.r = -2.0+2.5*(double)(i)/(double)(NPOINTS)+eps;
      c.i = 1.125*(double)(j)/(double)(NPOINTS)+eps;
      testpoint(c);
    }
  }
  wtime = omp_get_wtime() - wtime;
```

```
$ export OMP_SCHEDULE="dynamic,100"
$ ./mandel_par
```

default schedule	0.48 secs
schedule(dynamic,100)	0.39 secs
collapse(2) schedule(dynamic,100)	0.34 secs

Four threads on a dual core Apple laptop (Macbook air … 2.2 Ghz Intel Core i7 with 8 GB memory) and the gcc version 9.1. Times are the minimum time from three runs

Backup content

- Extra exercises
- Irregular parallelism and OpenMP tasks
- Worksharing Revisited
- Synchronization Revisited: Additional options for Mutual exclusion

Synchronization

Synchronization is used to impose order constraints between threads and to protect access to shared data

- High level synchronization included in the common core:
  - critical
  - barrier

Covered earlier

- Other, more advanced, synchronization operations:
  - atomic
  - ordered
  - flush
  - locks (both simple and nested)

Covered in this section

Synchronization: Atomic

- Atomic provides mutual exclusion but only applies to the update of a memory location (the update of X in the following example)

```
#pragma omp parallel
{
        double B;
        B =  DOIT();

 #pragma omp atomic
            X +=  big_ugly(B);
}
```

Synchronization: Atomic

- Atomic provides mutual exclusion but only applies to the update of a memory location (the update of X in the following example)

```
#pragma omp parallel
{
        double B, tmp;
        B =  DOIT();
        tmp = big_ugly(B);
 #pragma omp atomic
            X +=  tmp;
}
```

Atomic only protects the read/update of X

The OpenMP 3.1 Atomics (1 of 2)

- Atomic was expanded to cover the full range of common scenarios where you need to protect a memory operation so it occurs atomically:

```
# pragma omp atomic [read | write | update | capture]
```

- Atomic can protect loads

```
# pragma omp atomic read
    v = x;
```

- Atomic can protect stores

```
# pragma omp atomic write
    x = expr;
```

- Atomic can protect updates to a storage location (this is the default behavior … i.e. when you don't provide a clause)

```
# pragma omp atomic update
    x++;  or ++x;  or x--;  or –x;  or
    x binop= expr; or x = x binop expr;
```

This is the original OpenMP atomic

The OpenMP 3.1 Atomics (2 of 2)

- Atomic can protect the assignment of a value (its capture) AND an associated update operation:

  # pragma omp atomic capture

  statement or structured block

- Where the statement is one of the following forms:

  v = x++; v = ++x; v = x--; v = –x; v = x binop expr;

- Where the structured block is one of the following forms:

{v = x; x binop = expr;}
{v=x; x=x binop expr;}
{v = x; x++;}
{++x; v=x:}
{v = x; x--;}
{--x; v = x;}

{x binop = expr; v = x;}
{X = x binop expr; v = x;}
{v=x; ++x:}
{x++; v = x;}
{v= x; --x;}
{x--; v = x;}

The capture semantics in atomic were added to map onto common hardware supported atomic operations and to support modern lock free algorithms

Synchronization: Lock Routines

A lock implies a memory fence (a “flush”) of all thread visible variables

- Simple Lock routines:
  - A simple lock is available if it is unset.
    - omp_init_lock(), omp_set_lock(), omp_unset_lock(), omp_test_lock(), omp_destroy_lock()

- Nested Locks
  - A nested lock is available if it is unset or if it is set but owned by the thread executing the nested lock function
    - **omp_init_nest_lock(), omp_set_nest_lock(), omp_unset_nest_lock(), omp_test_nest_lock(), omp_destroy_nest_lock()**

Note: a thread always accesses the most recent copy of the lock, so you don’t need to use a flush on the lock variable.

Locks with hints were added in OpenMP 4.5 to suggest a lock strategy based on intended use (e.g. contended, uncontended, speculative, unspeculative)

Synchronization: Simple Locks Example

- Count odds and evens in an input array(x) of N random values.

```
int i, ix, even_count = 0, odd_count = 0;
omp_lock_t odd_lck,   even_lck;
omp_init_lock(&odd_lck);
omp_init_lock(&even_lck);

#pragma omp parallel for private(ix) shared(even_count, odd_count)
for(i=0; i<N; i++){
  ix = (int) x[i];  //truncate to int

  if(((int) x[i])%2 == 0) {
      omp_set_lock(&even_lck);
        even_count++;
      omp_unset_lock(&even_lck);
  }
  else{
      omp_set_lock(&odd_lck);
        odd_count++;
      omp_unset_lock(&odd_lck);
  }
 }
 omp_destroy_lock(&odd_lck);
 omp_destroy_lock(&even_lck);
}
```

One lock per case … even and odd

Enforce mutual exclusion updates, but in parallel for each case.

Free-up storage when done.

Exercise

- In the file hist.c, we provide a program that generates a large array of random numbers and then generates a histogram of values.
- This is a ”quick and informal” way to test a random number generator … if all goes well the bins of the histogram should be the same size.
- Parallelize the filling of the histogram You must assure that your program is race free and gets the same result as the sequential program.
- Using everything we've covered today, manage updates to shared data in multiple ways. Try to minimize the time to generate the histogram.
- Time ONLY the assignment to the histogram. Can you beat the sequential time?

```
#define     num_trials    1000000 // number of x values
#define     num_buckets   50      // number of buckets in histogram
static long xlow        = 0.0;     // low end of x range
static long xhi         = 100.0;   // High end of x range

int main (){
   double x[num_trials];     // array used to assign counters in the historgram
   long   hist[num_buckets]; // the histogram
   double bucket_width;      // the width of each bucket in the histogram
   double time;

   seed(xlow, xhi);  // seed the random number generator over range of x
   bucket_width = (xhi-xlow)/(double)num_buckets;

   // fill the array. << code not shown >>

  // initialize the histogram << code not shown >>

  // Assign x values to the right histogram bucket
   time = omp_get_wtime();
   for(int i=0;i<num_trials;i++){

      long ival = (long) (x[i] - xlow)/bucket_width;

      hist[ival]++;

   }

  time = omp_get_wtime() - time;

   // compute statistics and output results << code not shown >>
   return 0;
}
```

Only focus on this part of the program

Histogram Program: Critical section

- A critical section means that only one thread at a time can update a histogram bin … but this effectively serializes the loops and adds huge overhead as the runtime manages all the threads waiting for their turn for the update.

```
#pragma omp parallel for
 for(i=0;i<NVALS;i++){
     ival = (int)  x[i];
     #pragma omp critical
         hist[ival]++;
}
```

Easy to write and correct, but terrible performance

Histogram program: one lock per histogram bin

- Example: conflicts are rare, but to play it safe, we must assure mutual exclusion for updates to histogram elements.

```
#pragma omp parallel for
 for(i=0;i<NBUCKETS; i++){
       omp_init_lock(&hist_locks[i]);    hist[i] = 0;
 }
 #pragma omp parallel for
 for(i=0;i<NVALS;i++){
     ival = (int)  x[i];
     omp_set_lock(&hist_locks[ival]);
          hist[ival]++;
     omp_unset_lock(&hist_locks[ival]);
   }

 #pragma omp parallel for
for(i=0;i<NBUCKETS; i++)
  omp_destroy_lock(&hist_locks[i]);
```

One lock per element of hist

Enforce mutual exclusion on update to hist array

Free-up storage when done.

Histogram program: reduction with an array

- We can give each thread a copy of the histogram, they can fill them in parallel, and then combine them when done

```
#pragma omp parallel for reduction(+:hist[0:Nbins])
 for(i=0;i<NVALS;i++){
     ival = (int)  x[i];
     hist[ival]++;
}
```

Easy to write and correct, Uses a lot of memory on the stack, but its fast … sometimes faster than the serial method.

sequential	0.0019 secs
critical	0.079 secs
Locks per bin	0.029 secs
Reduction, replicated histogram array	0.00097 secs

1000000 random values in X sorted into 50 bins. Four threads on a dual core Apple laptop (Macbook air … 2.2 Ghz Intel Core i7 with 8 GB memory) and the gcc version 9.1. Times are for the above loop only (we do not time set-up for locks, destruction of locks or anything else)