

An Introduction to Parallel Programming with OpenMP

Tim Mattson



Tim's Backyard around sunset

An Introduction to me

I'm just a simple kayak instructor

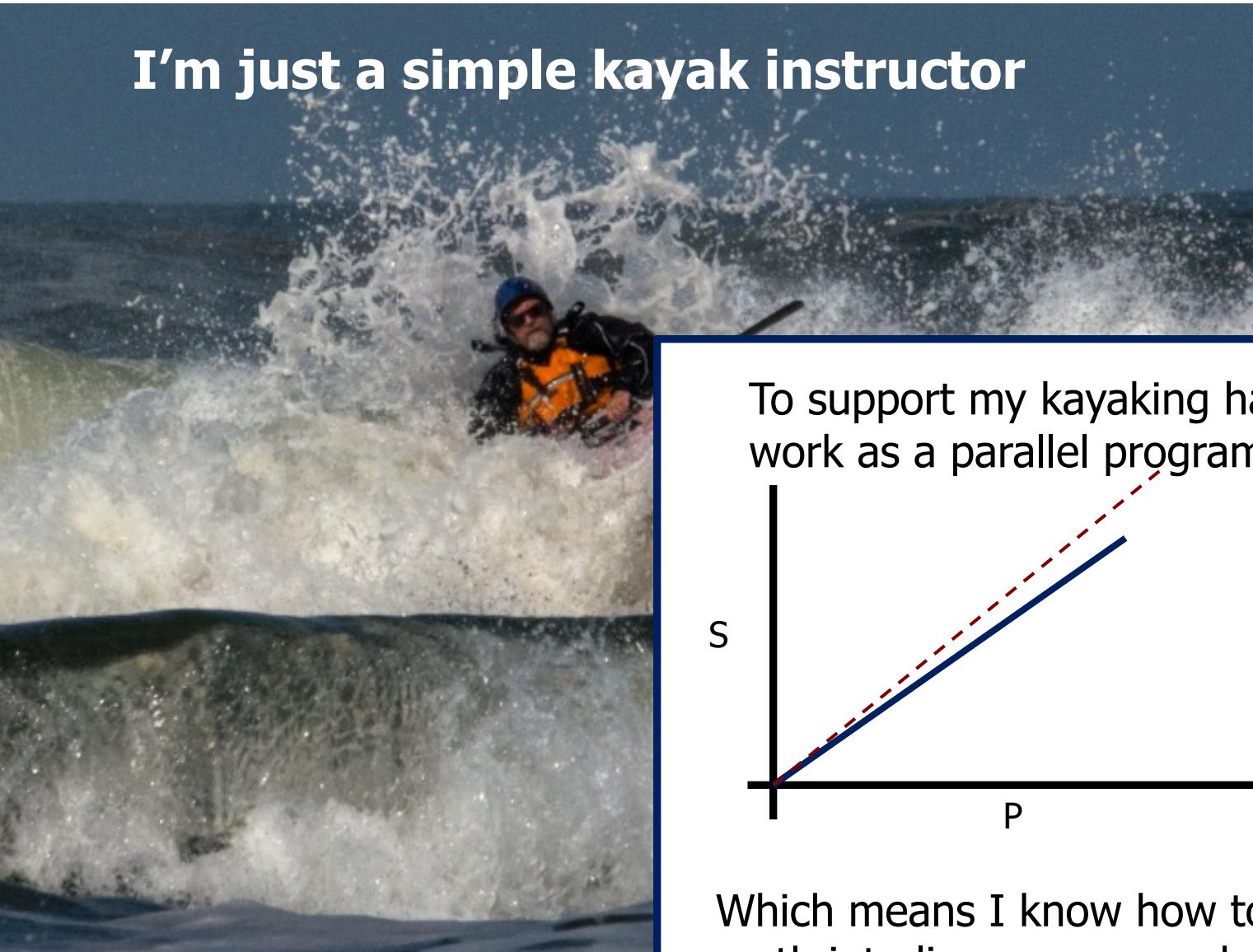
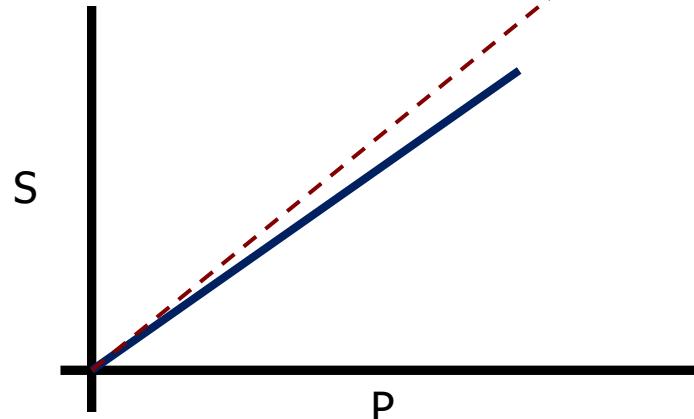


Photo © by Greg Clopton, 2014

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

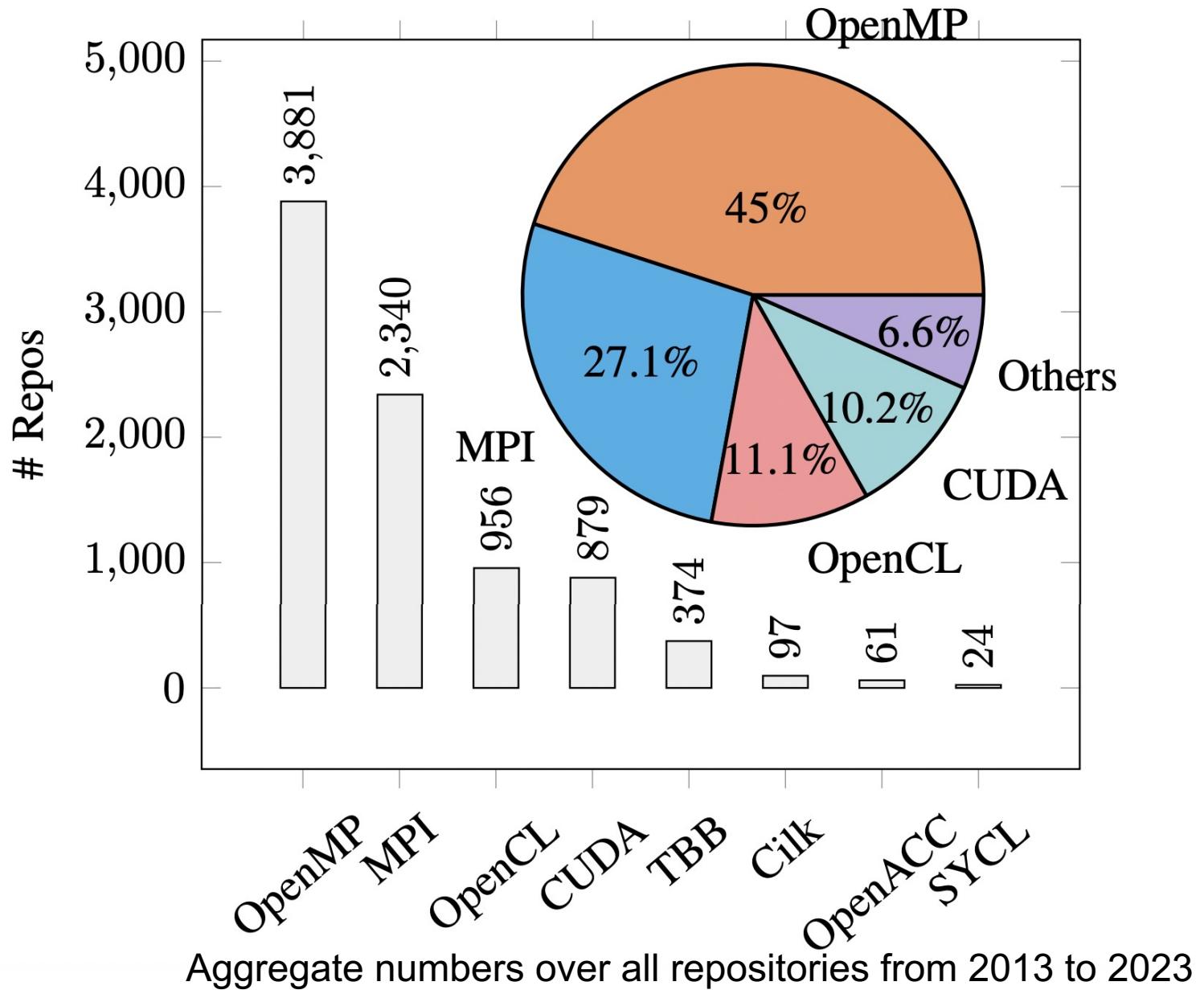


Which means I know how to turn math into lines on a speedup plot

**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?**

OpenMP is the most popular parallel programming model in use today

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



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

Outline

OpenMP®

- ➡ • Introduction to OpenMP
 - Creating Threads
 - Synchronization
 - Parallel Loops
 - Data Environment
 - Memory Model
 - Irregular Parallelism and Tasks
 - Recap
 - Beyond the Common Core:
 - Worksharing Revisited
 - Additional options for Mutual exclusion
 - Thread Affinity and Data Locality

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

cal

- 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)

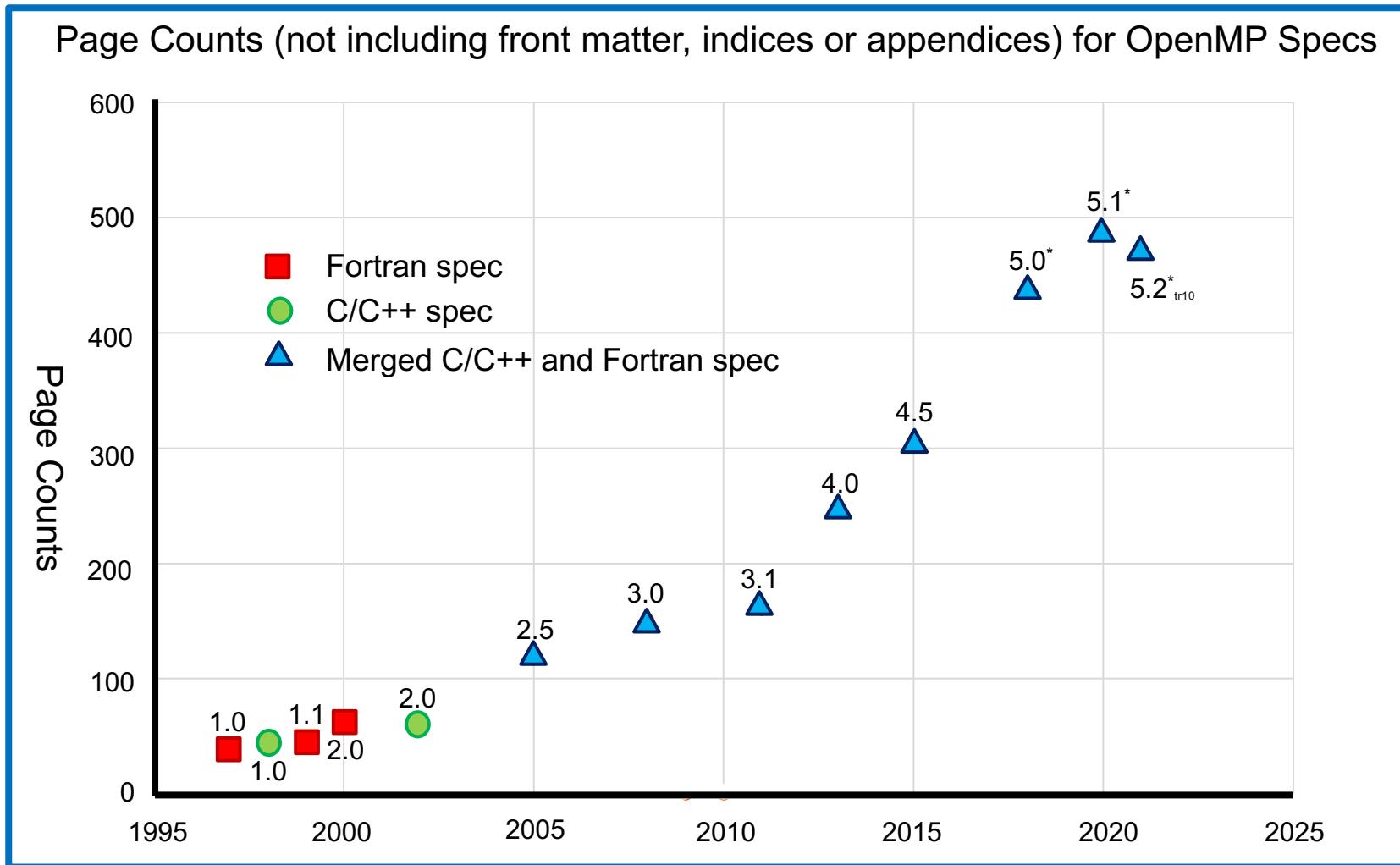
#pragma omp atomic seq_cst

Nthrds = OMP_GET_NUM_PROCS()

omp_set_lock(lck)

The Growth of Complexity in OpenMP

Our goal in 1997 ... A simple interface for application programmers

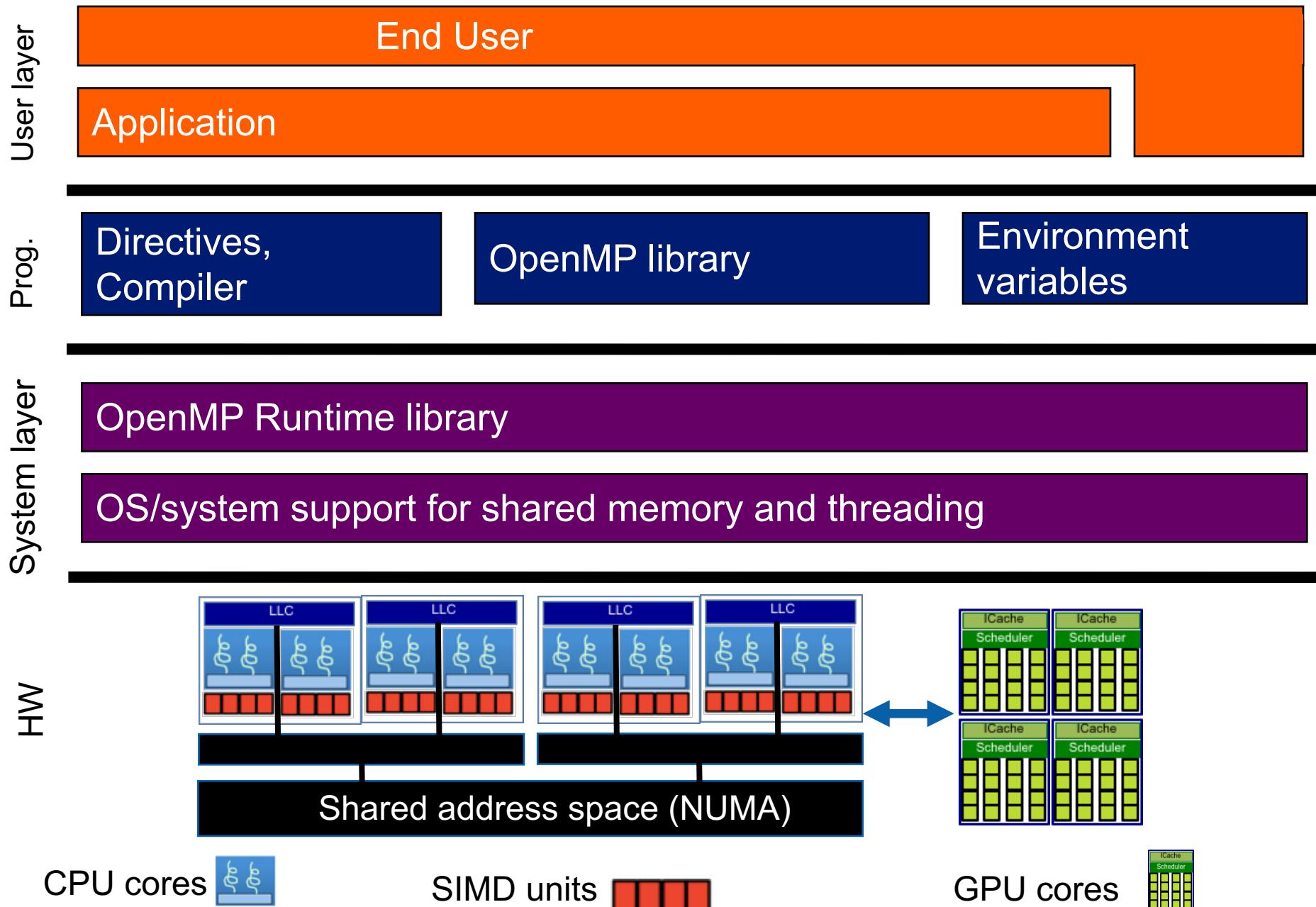


The full spec is overwhelming. We focus on the Common Core: the 21 items most people restrict themselves to

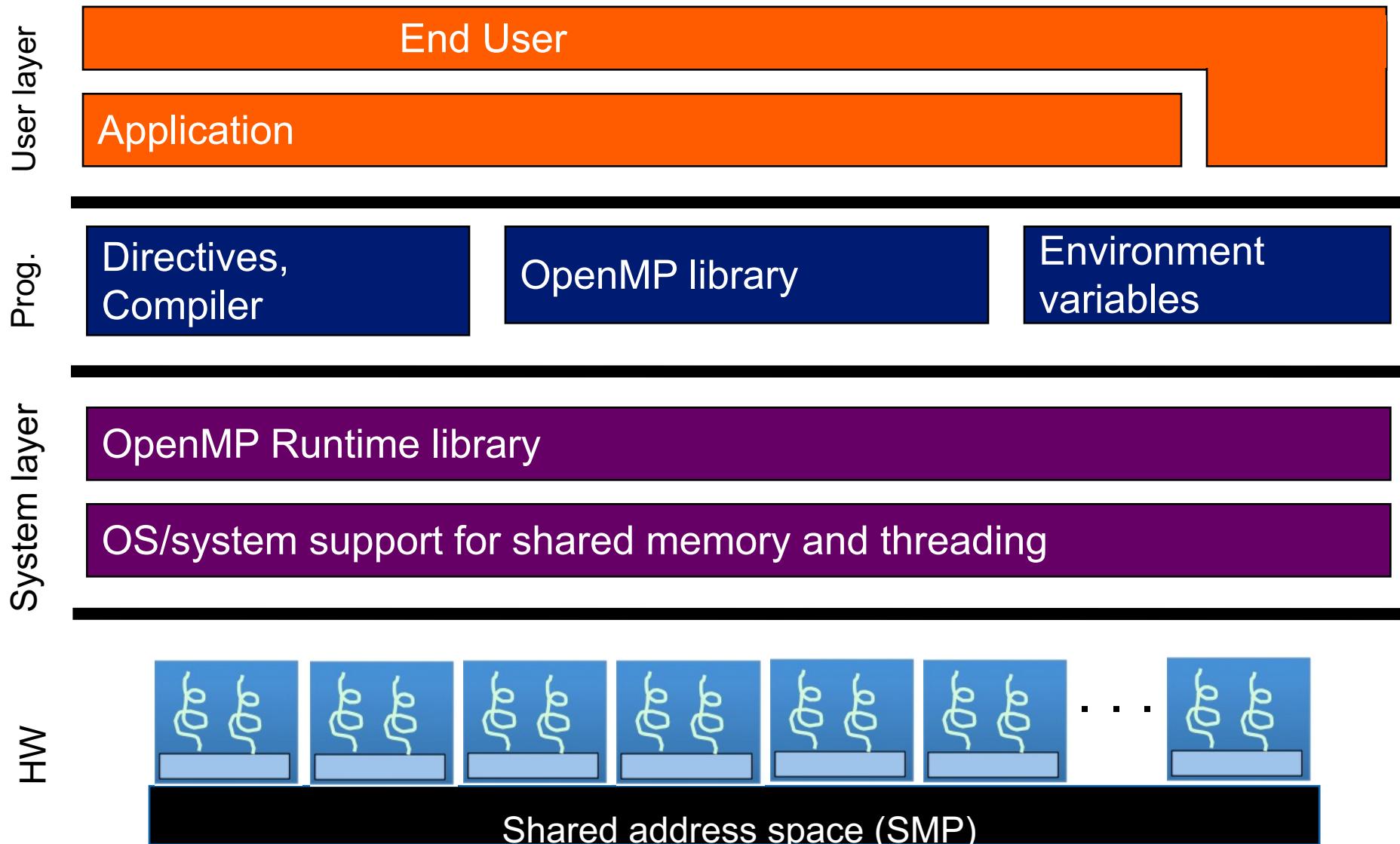
The OpenMP Common Core: Most OpenMP programs only use these 21 items

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	
<code>#pragma omp construct [clause [clause]...]</code>	<code>!\$OMP construct [clause [clause] ...]</code>
Example	
<code>#pragma omp parallel private(x)</code> { }	<code>!\$OMP PARALLEL PRIVATE(X)</code> <code>!\$OMP END PARALLEL</code>
Function prototypes and types:	
<code>#include <omp.h></code>	<code>use OMP_LIB</code>

- 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 -qopenmp	Intel (Linux@NERSC)
icc -fopenmp	Intel (Linux, OSX)

Solution

A Multi-Threaded “Hello World” Program

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

```
#include <omp.h> ← OpenMP include file
#include <stdio.h>
int main()
{
#pragma omp parallel ← Parallel region with
    {                                default number of threads
        printf(" hello ");
        printf(" world \n");
    }                                End of the Parallel region
}
```

Sample Output:

hello hello world

world

hello hello world

world

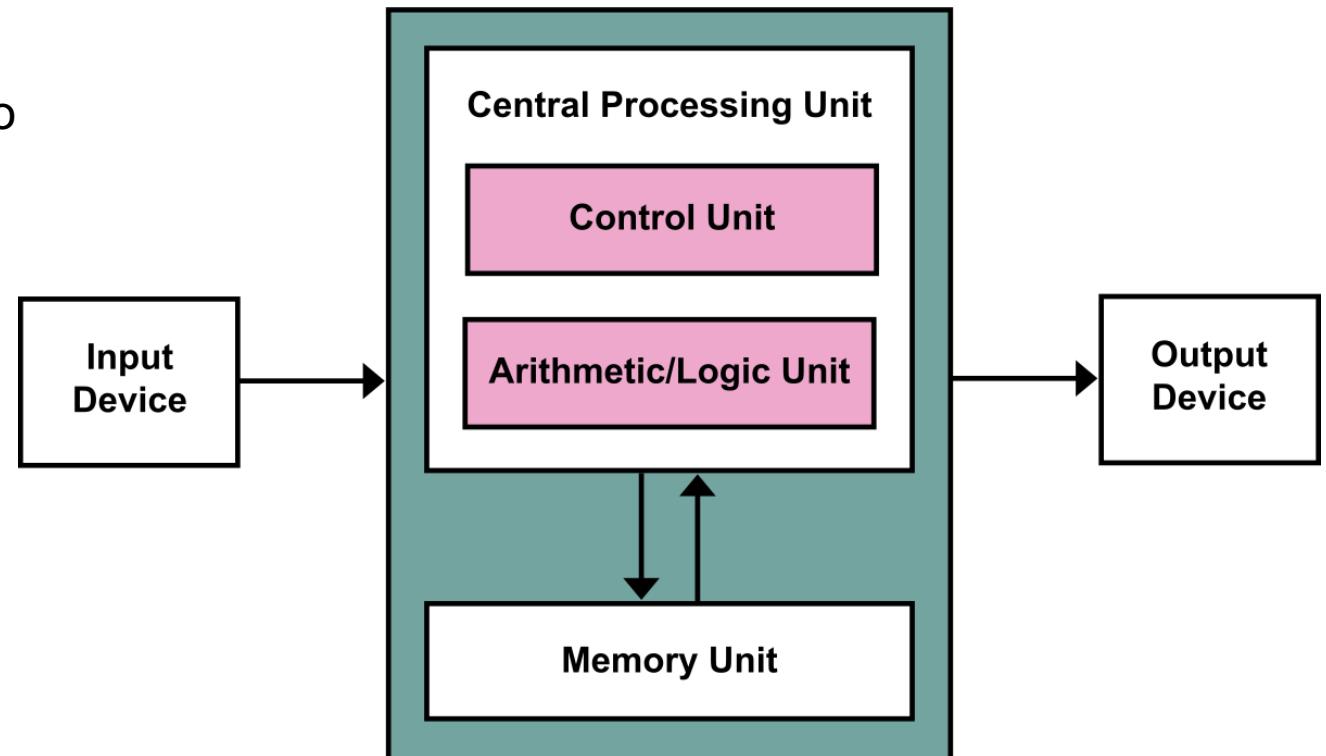
The statements are interleaved based on how the operating system schedules the threads

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:**

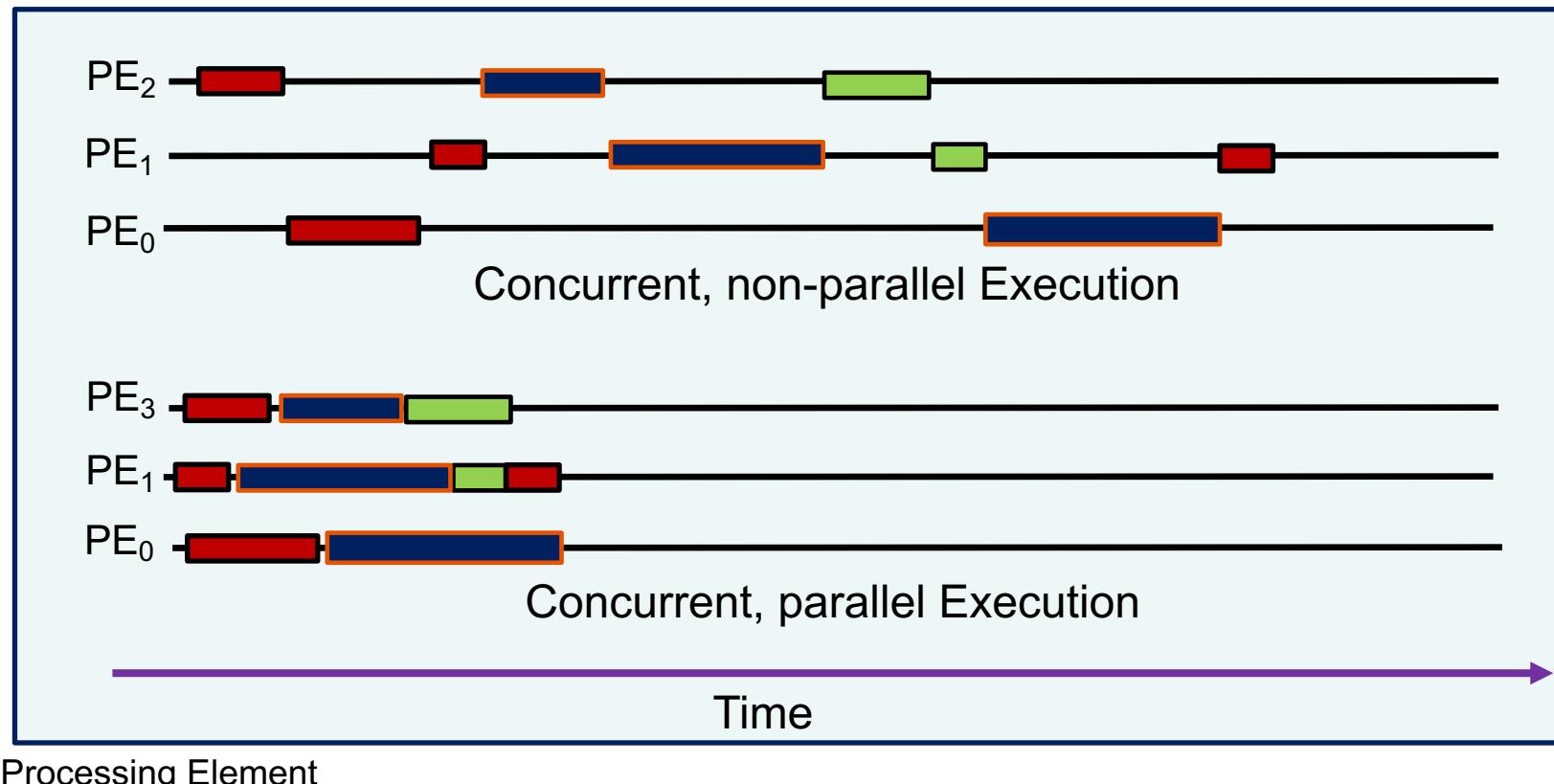
- A task that is available to be scheduled for execution. When the task is moving through its sequence of instructions, we say it is making **forward progress**

- **Fair scheduling:**

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

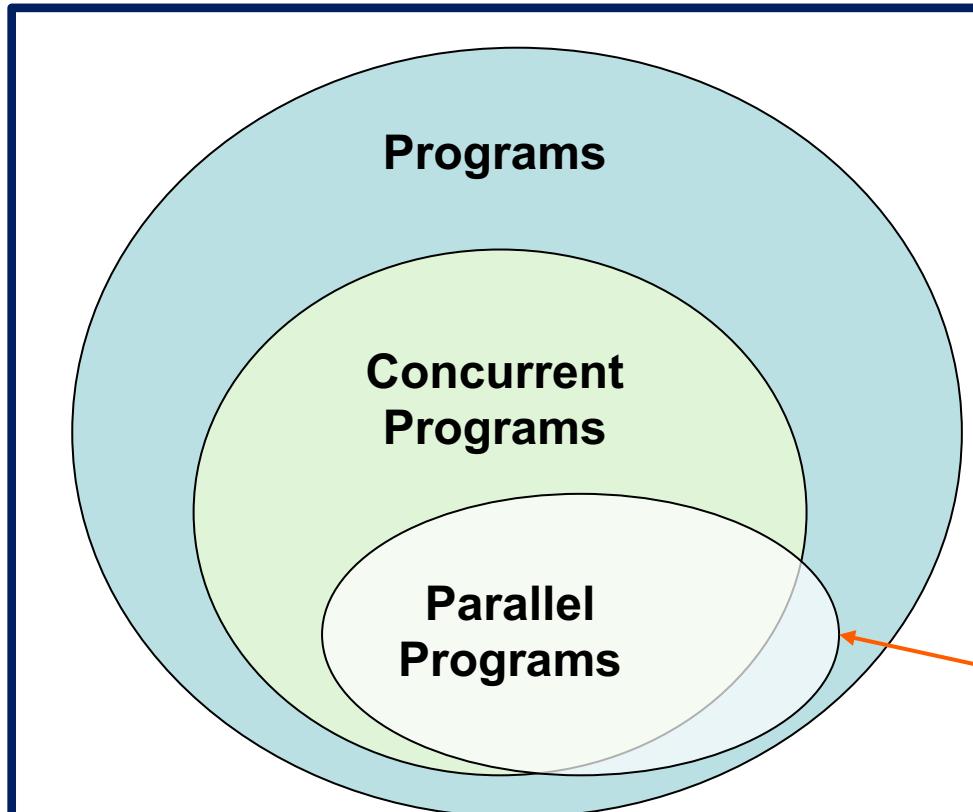
Concurrency vs. Parallelism

- 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.



Concurrency vs. Parallelism

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 - 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.
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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.

Outline

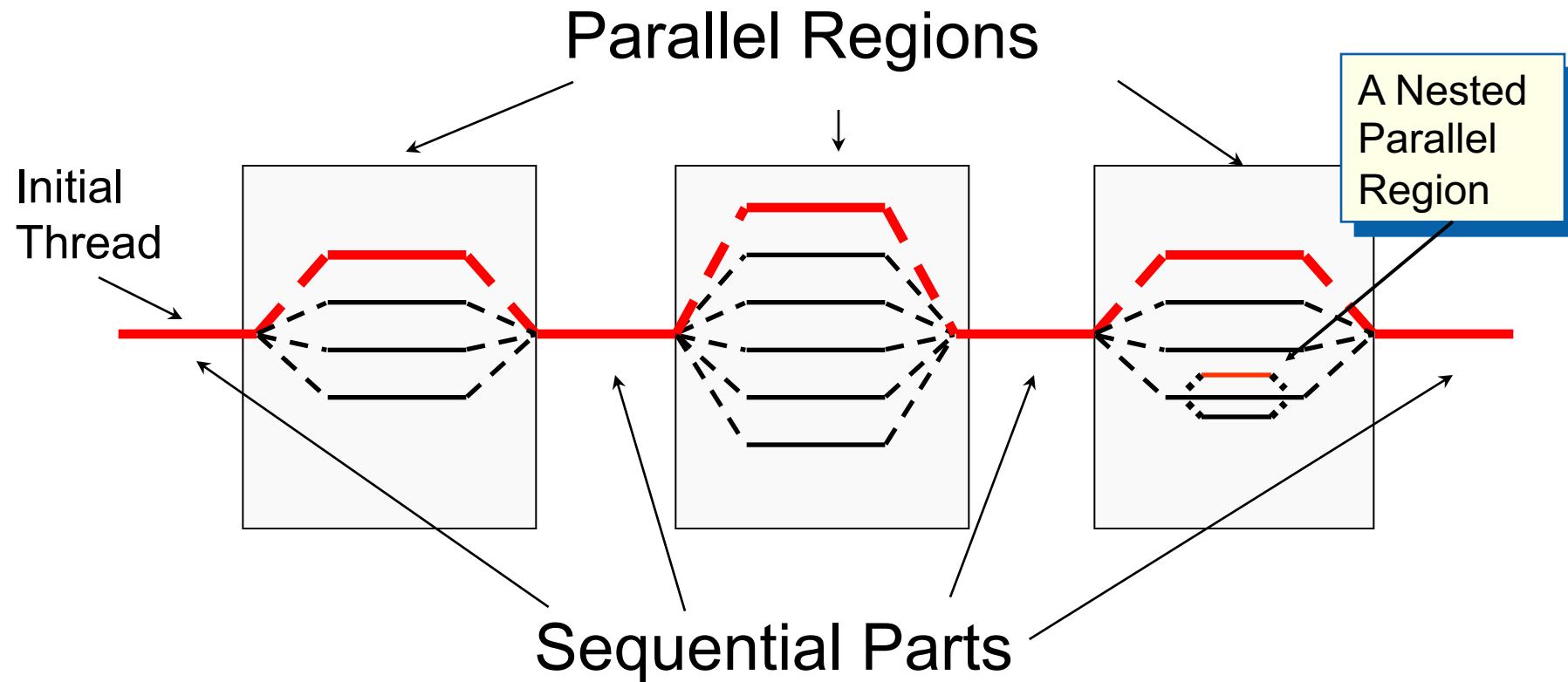
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OpenMP Execution model:

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 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();
    pooh(ID,A);
}
```

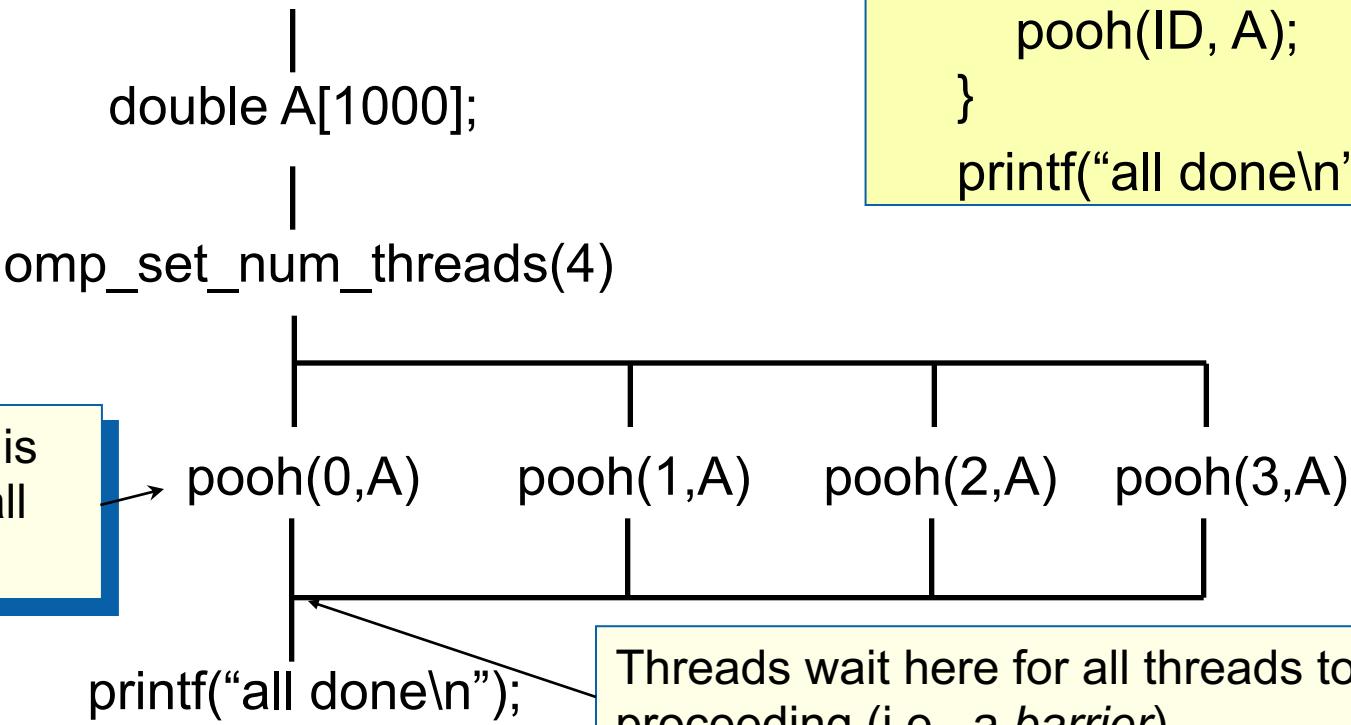
Runtime function to request a certain number of threads

Runtime function returning a thread ID

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

Thread Creation: Parallel Regions Example

- Each thread executes the same code redundantly.



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

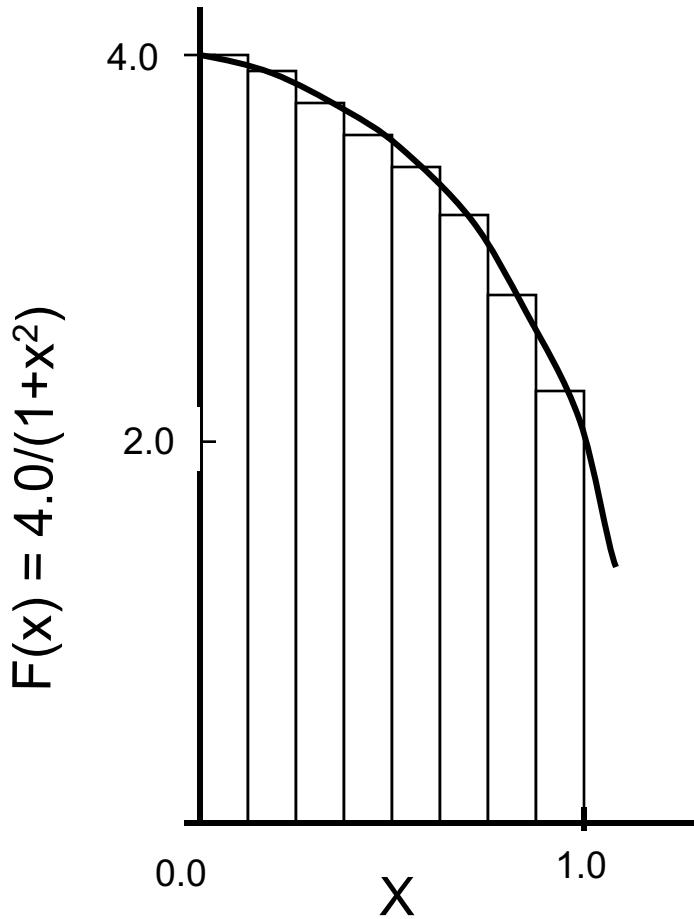
- Each thread calls `pooh(ID,A)` for $ID = 0$ to $nthrds-1$

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;
}
```

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

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();` ← Number of threads in the team
- `int omp_get_thread_num();` → Thread ID or rank
- `double omp_get_wtime();` ← Time in seconds since a fixed point in the past
- `omp_set_num_threads();`

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
 - int 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

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.

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;
}
```

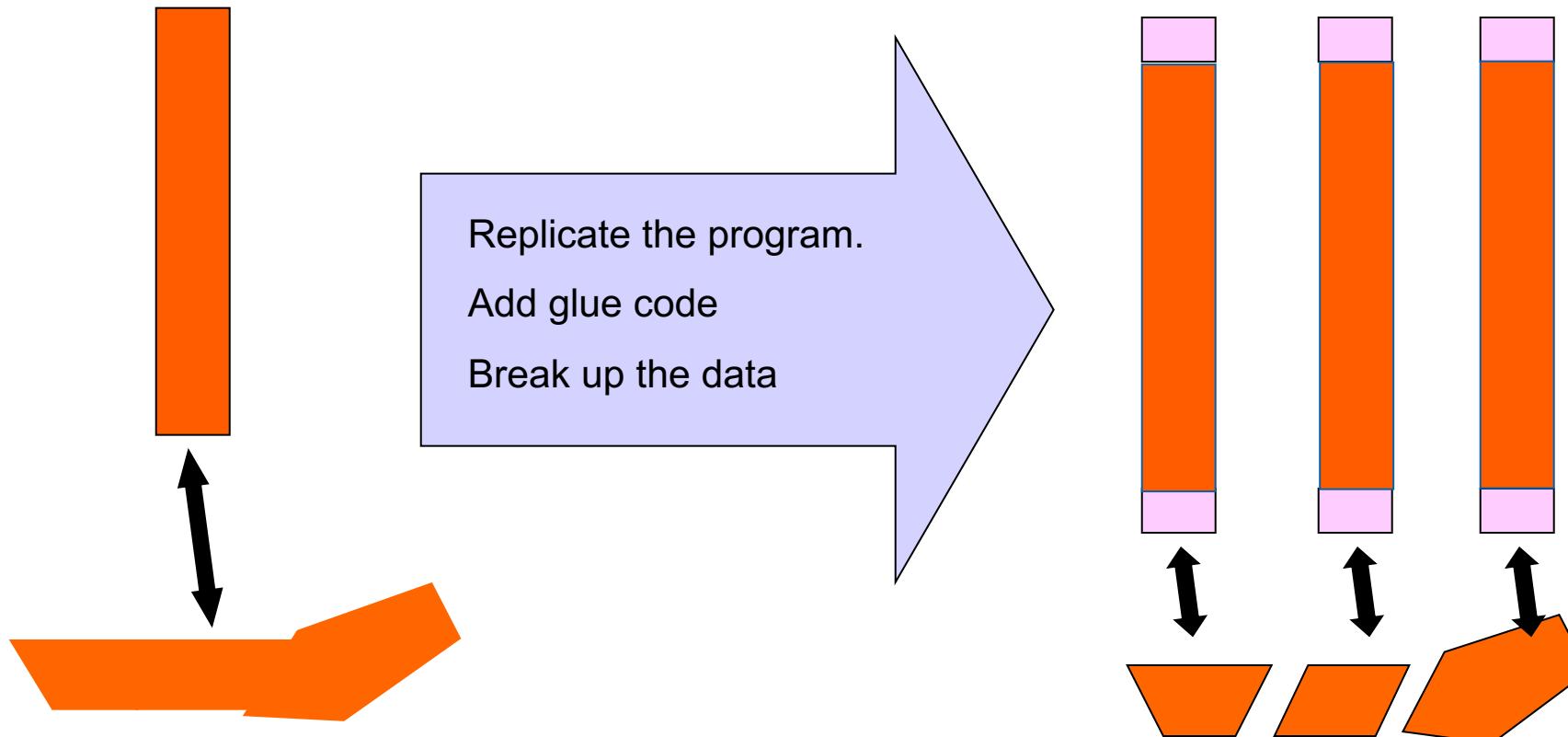
threads	1 st SPMD*
1	1.86
2	1.03
3	1.08
4	0.97

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.

How do we describe performance 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

...

Consume Results

Compute T_N

Ideally Cut
runtime by $\sim 1/P$

(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.
- Perfect Linear Speedup: happens when no parallel overhead and algorithm is 100% parallel.
- Efficiency: How well does your observed speedup compare to the ideal case?

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

$$S(P) = P$$

$$\varepsilon(P) = \frac{S(P)}{P}$$

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 $(1 - \alpha)$ then the speedup is:

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

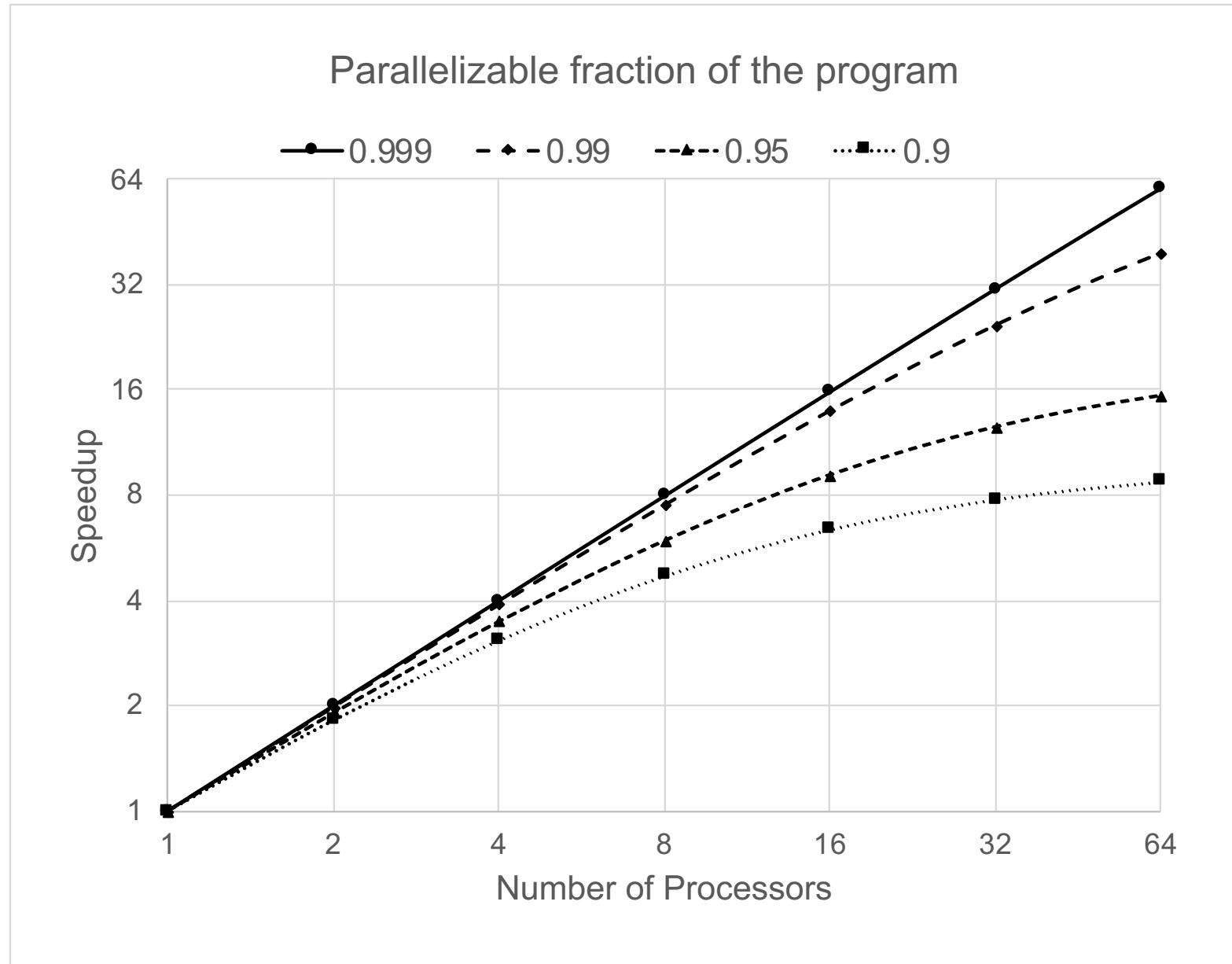
- If you had an unlimited number of processors: $P \rightarrow \infty$

- The maximum possible speedup is:

$$S = \frac{1}{\alpha}$$

Amdahl's
Law

Amdahl's Law ... It's not just about the maximum speedup



So now you should understand my silly introduction slide.

Introduction

I'm just a simple kayak instructor

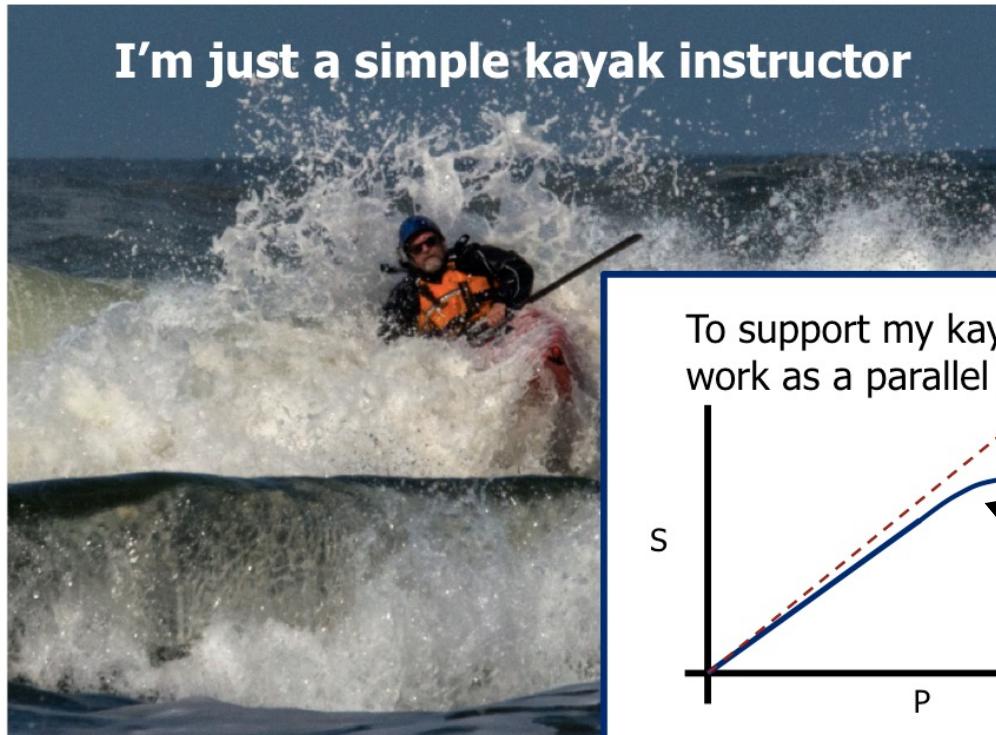
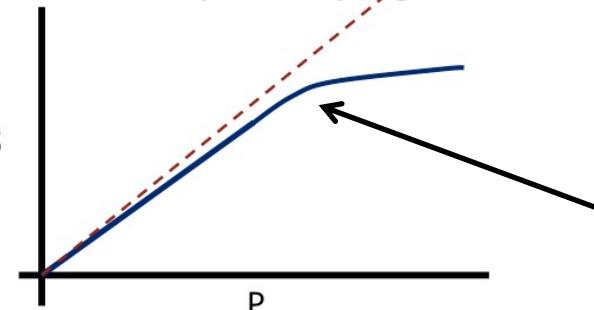


Photo © by Greg Clopton, 2014

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.

**.... Now that we know how to describe
performance for parallel computations,
lets get back to OpenMP**

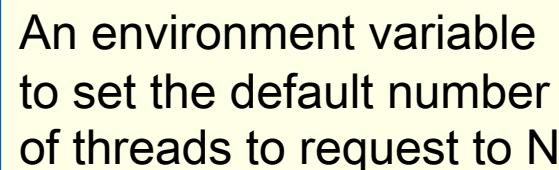
Internal control variables and how to control the number of threads in a team

- We've used the following construct to control the number of threads. (e.g. to request 12 threads):
 - `omp_set_num_threads(12)`
- What does `omp_set_num_threads()` actually do?
 - It resets an “internal control variable” the system queries to select the default number of threads to request on subsequent parallel constructs.
- Is there an easier way to change this internal control variable ... perhaps one that doesn't require re-compilation? Yes.
 - When an OpenMP program starts up, it queries an environment variable `OMP_NUM_THREADS` and sets the appropriate internal control variable to the value of **OMP_NUM_THREADS**
 - For example, to set the initial, default number of threads to request in OpenMP from my apple laptop
 - > **export OMP_NUM_THREADS=12**

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
to set the default number
of threads to request to N

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;
}
```

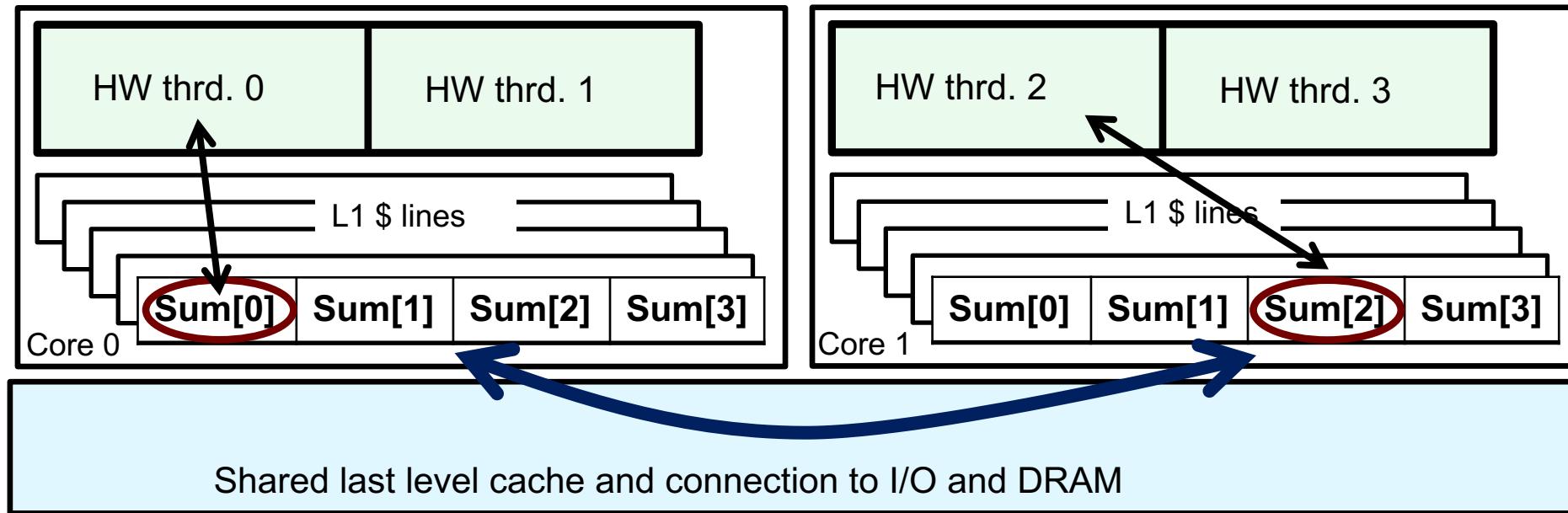
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*SPMD: Single Program Multiple Data

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	1 st SPMD	1 st 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.

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OpenMP®

- Introduction to OpenMP
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- Parallel Loops
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- Irregular Parallelism and Tasks
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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 must 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	1 st 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; ← Create a scalar local to each
    id = omp_get_thread_num();                                thread to accumulate partial sums.
    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); ← No array, so no false sharing.
    }
    #pragma omp critical
    pi += sum * step; ← 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?

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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];}
```

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();  
}
```

These are equivalent

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

```
int i, j, A[MAX];
j = 5;
for (i=0;i< MAX; i++) {
    j +=2;
    A[i] = big(j);
}
```

Note: loop index
“i” is private by
default

Remove loop
carried
dependence

```
int i, A[MAX];
#pragma omp parallel for
for (i=0;i< MAX; i++) {
    int j = 5 + 2*(i+1);
    A[i] = big(j);
}
```

Reduction

- How do we handle this case?

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

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
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
and array-sections as reduction variables
(we just don't cover those 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;           ← Create a scalar local to each thread to hold
        #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), ← Break up loop iterations
        }                                and assign them to
    }                                    threads ... setting up a
    pi = step * sum;                   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

```
#include <omp.h>
static long num_steps = 100000000;
void main ()
{
    int i;      double x, pi, sum;
    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;
}
```

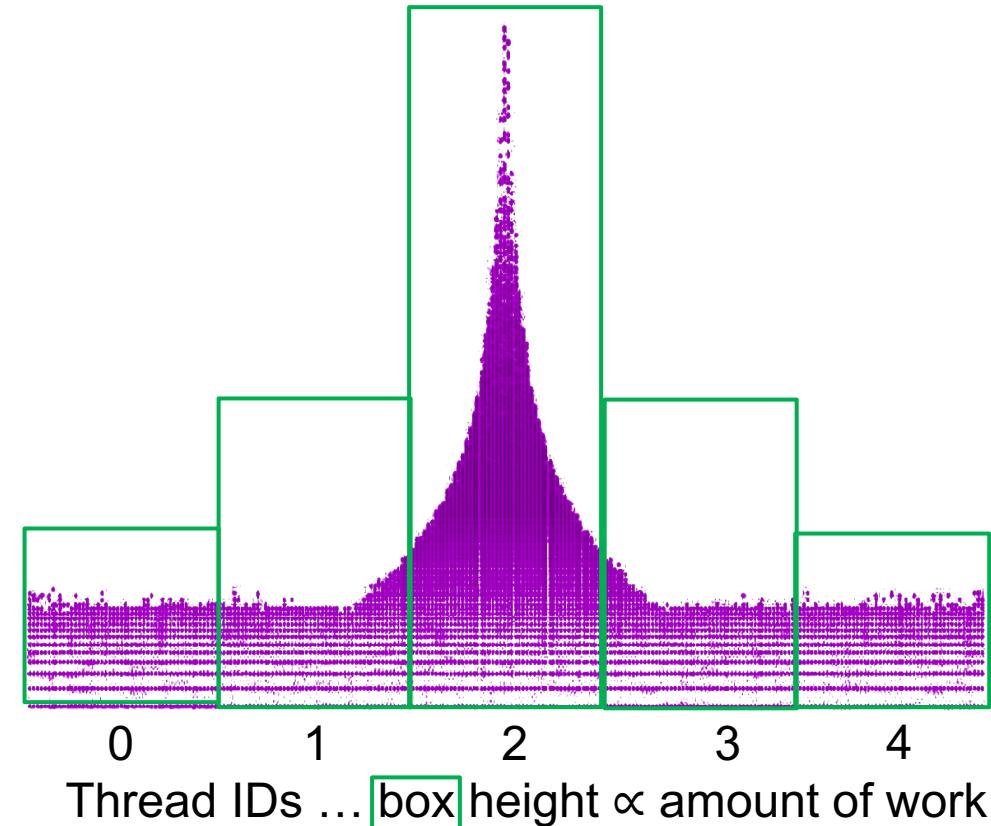
threads	1 st SPMD	1 st SPMD padded	SPMD critical	PI Loop
1	1.86	1.86	1.87	1.91
2	1.03	1.01	1.00	1.02
3	1.08	0.69	0.68	0.80
4	0.97	0.53	0.53	0.68

*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**

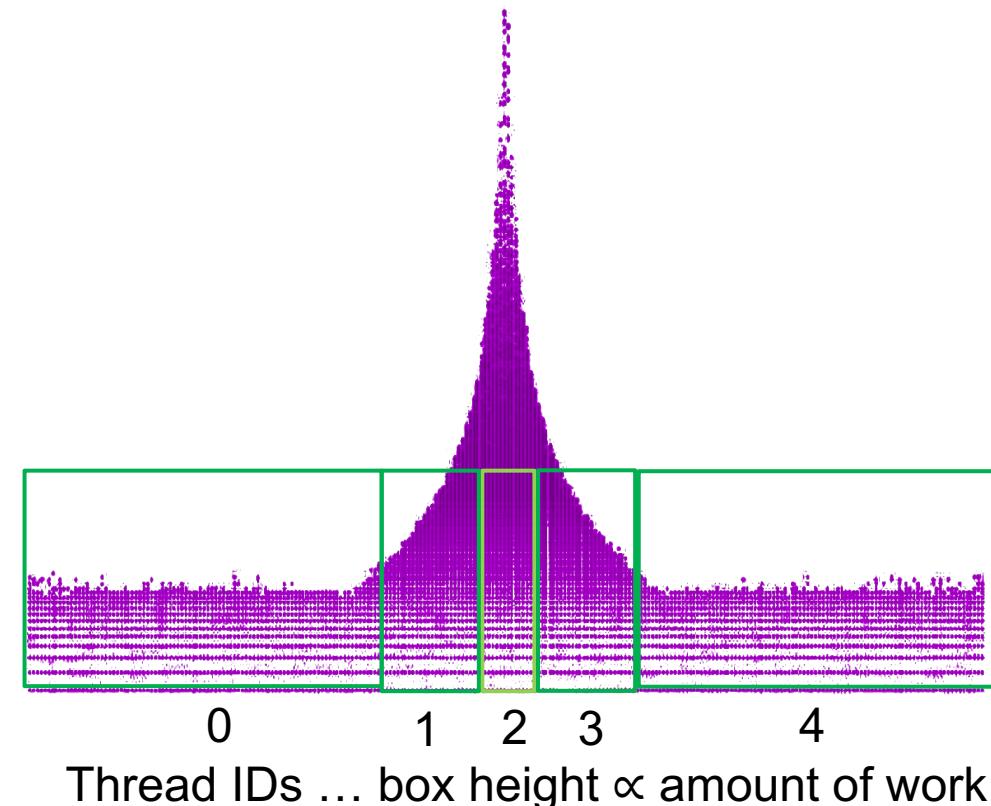
Load Balancing

- 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.



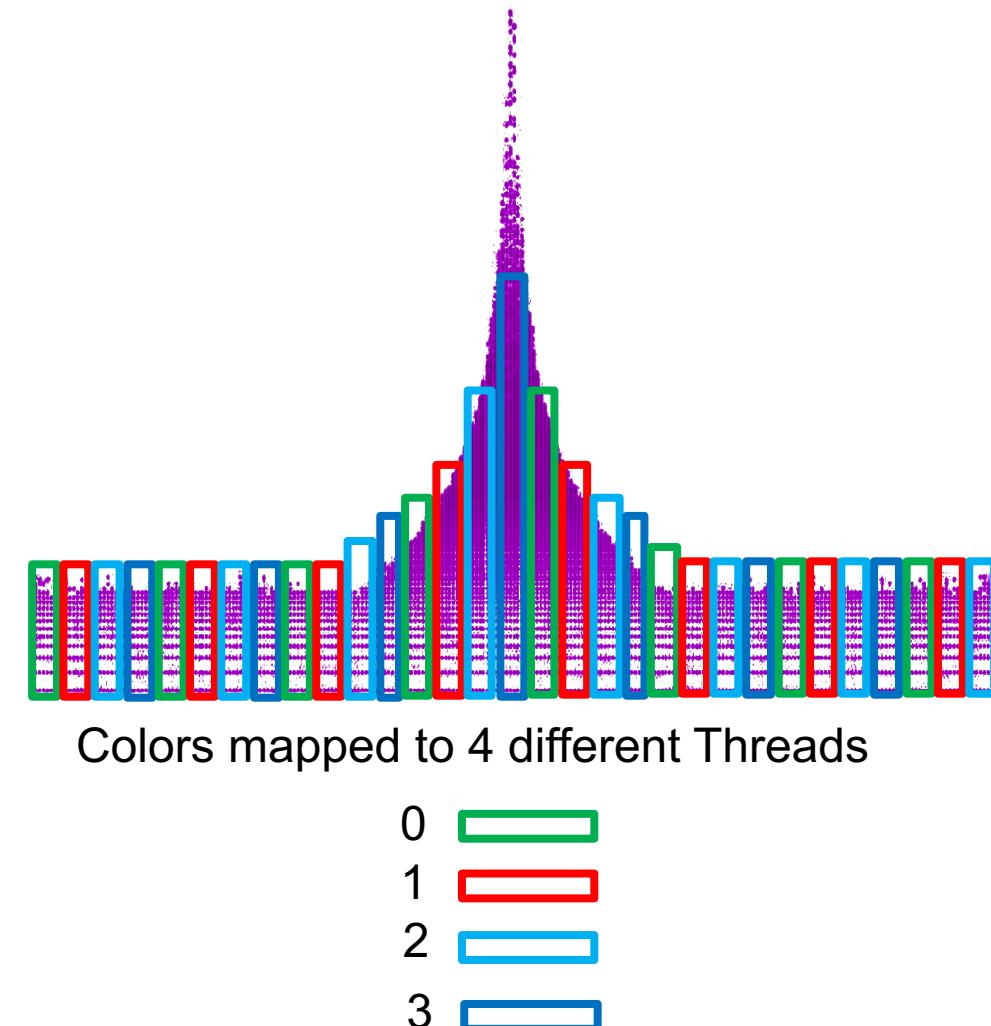
Load Balancing

- 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.



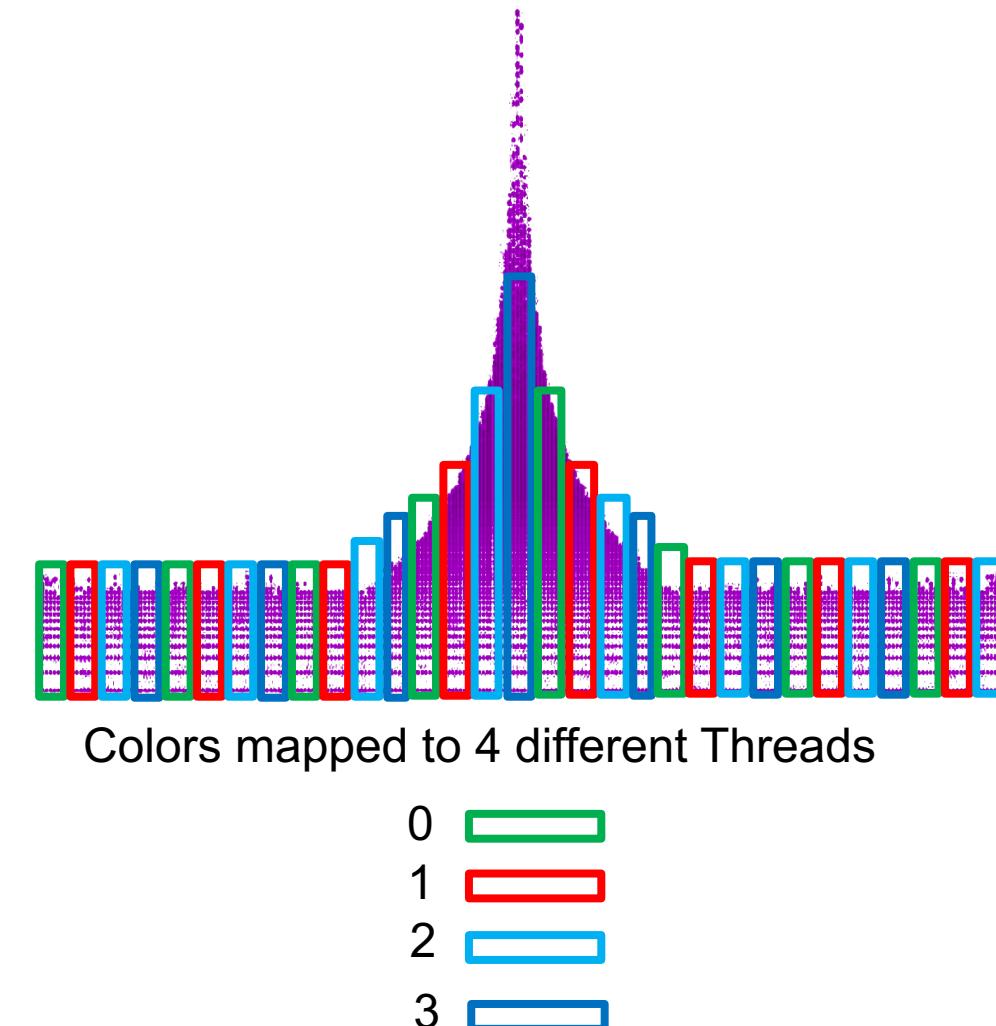
Load Balancing

- 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

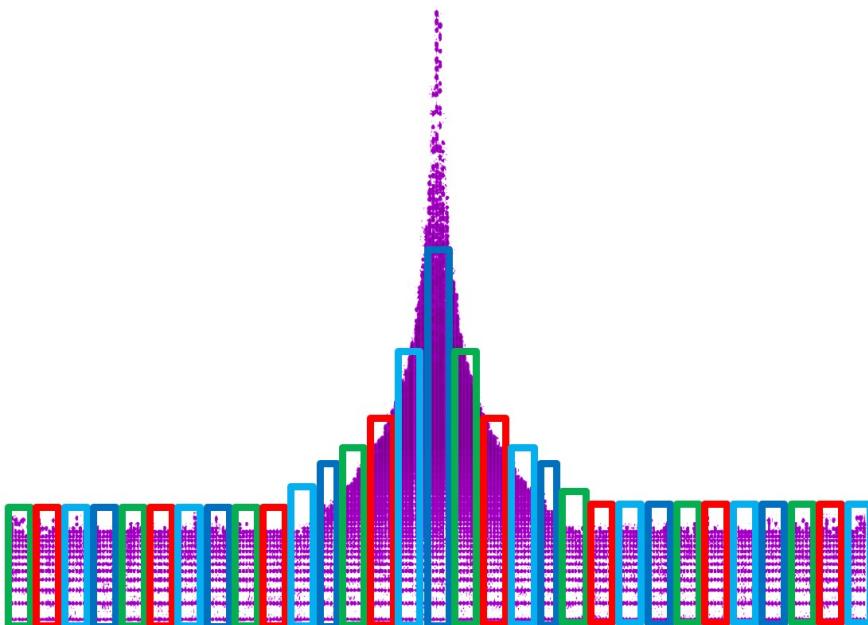
- The schedule clause affects how loop iterations are mapped onto threads
 - **schedule(static [,chunk])**
 - Deal-out blocks of iterations of size “chunk” to each thread.
 - **schedule(dynamic[,chunk])**
 - Each thread grabs “chunk” iterations off a queue until all iterations have been handled.
- Example: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

Schedule Clause	When To Use	
STATIC	Pre-determined and predictable by the programmer	Least work at runtime : scheduling done at compile-time
DYNAMIC	Unpredictable, highly variable work per iteration	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)` →

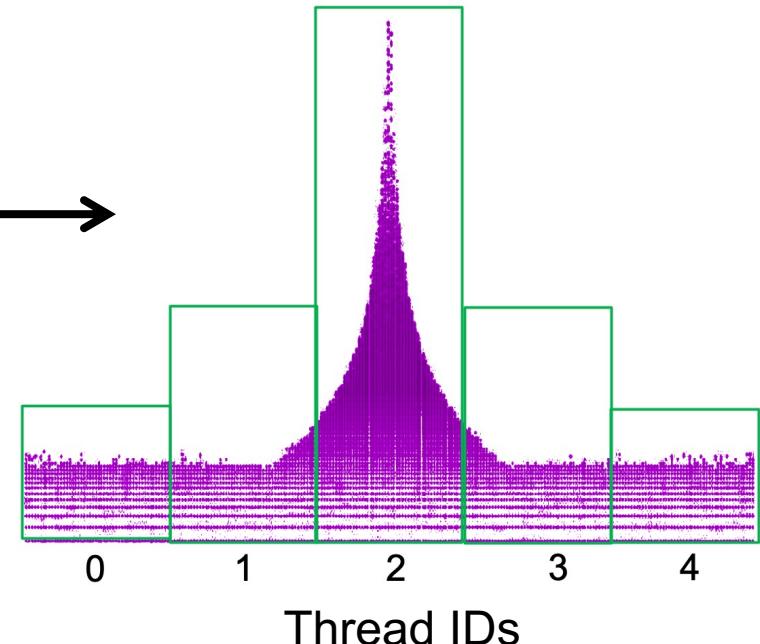


0	█
1	█
2	█
3	█



`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

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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.

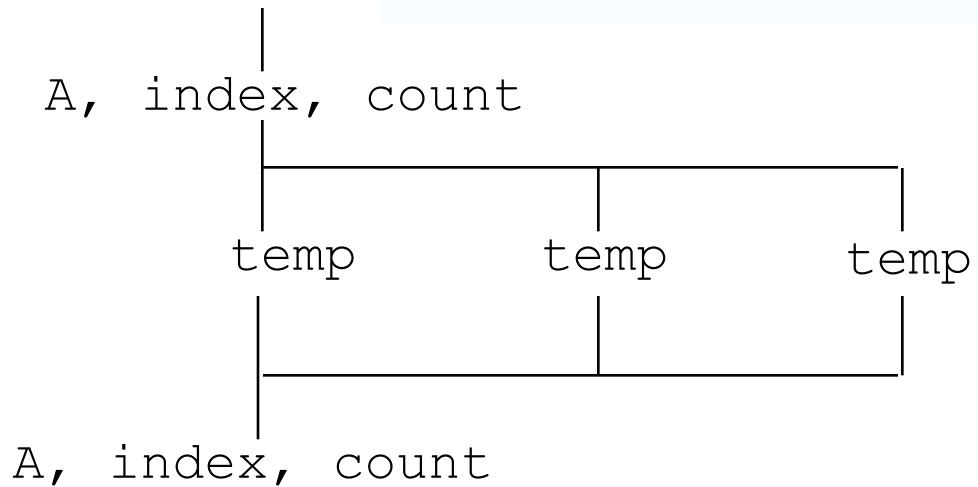
Data Sharing: Examples

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

A, index and count are shared by all threads.

temp is local to each thread

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



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

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

```
incr = 0;  
#pragma omp parallel for private(incr)  
for (i = 0; i <= MAX; i++) {  
    if ((i%2)==0) incr++;  
    A[i] = incr;  
}  
printf(" incr= %d\n", incr);
```

incr was not initialized

incr 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

Data sharing: A data environment test

- Consider this example of PRIVATE and FIRSTPRIVATE

```
variables: A = 1, B = 1, C = 1  
#pragma omp parallel private(B) firstprivate(C)
```

- Are A,B,C private to each thread or shared inside the parallel region?
- What are their initial values inside and values after the parallel region?

Inside this parallel region ...

- “A” is shared by all threads; equals 1
- “B” and “C” are private to each thread.
 - B’s initial value is undefined
 - C’s initial value equals 1

Following the parallel region ...

- B and C revert to their original values of 1
- A is either 1 or the value it was set to inside the parallel region

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.

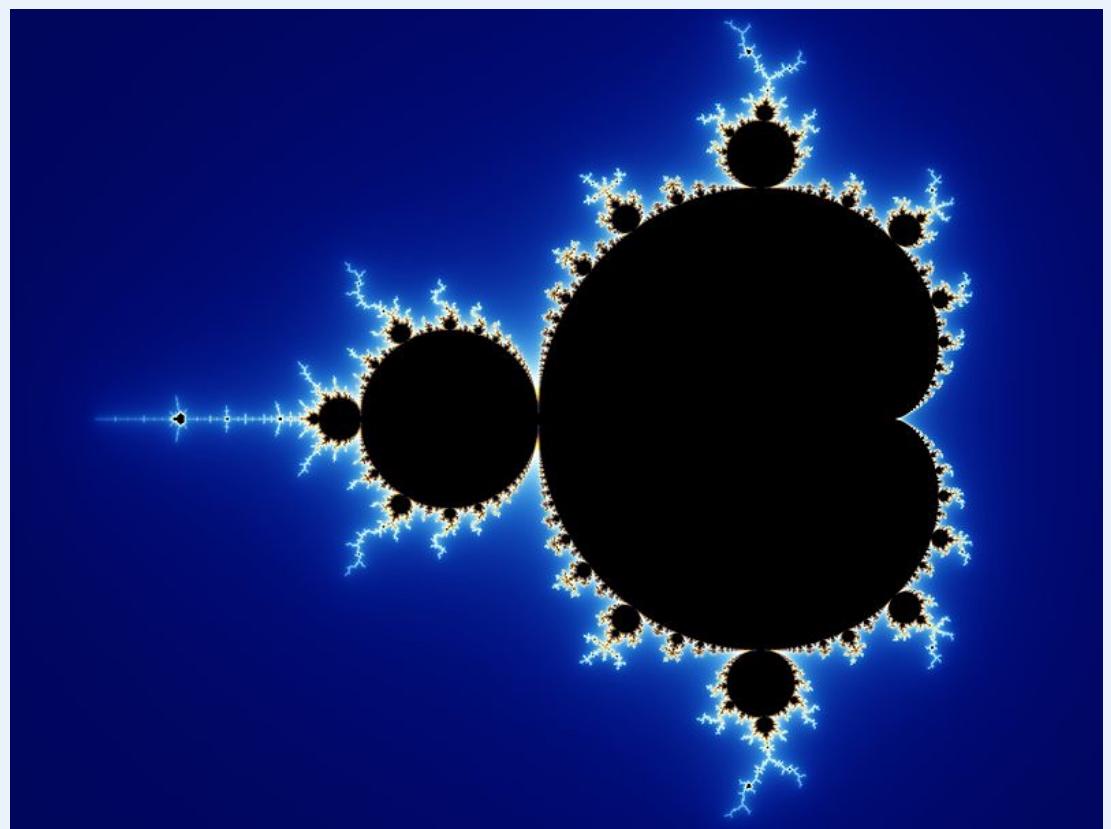


Image Source: Created by Wolfgang Beyer with the program Ultra Fractal 3. - Own work, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=321973>

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 $z_0 = 0$.

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;
}
```

Data Sharing: Default clause

- **default(none)**: Forces you to define the storage attributes for variables that appear inside the static extent of the construct ... if you fail the compiler will complain. Good programming practice!
- You can put the default clause on parallel and parallel + workshare constructs.

The static extent is the code in the compilation unit that contains the construct.

```
#include <omp.h>
int main()
{
    int i, j=5;    double x=0.0, y=42.0;
    #pragma omp parallel for default(none) reduction(*:x)
    for (i=0;i<N;i++){
        for(j=0; j<3; j++)
            x+= foobar(i, j, y);
    }
    printf(" x is %f\n", (float)x);
}
```

The compiler would complain about j and y, which is important since you don't want j to be shared

The full OpenMP specification has other versions of the default clause, but they are not used very often so we skip them in the common core

Data Sharing: Private and the original variable

- The original variable's value is unspecified if it is referenced outside of the construct
 - Implementations may reference the original variable or a copy a dangerous programming practice!
 - For example, consider what would happen if the compiler inlined work()?

```
int tmp;
void danger() {
    tmp = 0;
#pragma omp parallel private(tmp)
    work();
    printf("%d\n", tmp);
}
```

tmp has unspecified value

```
extern int tmp;
void work() {
    tmp = 5;
}
```

unspecified which
copy of tmp

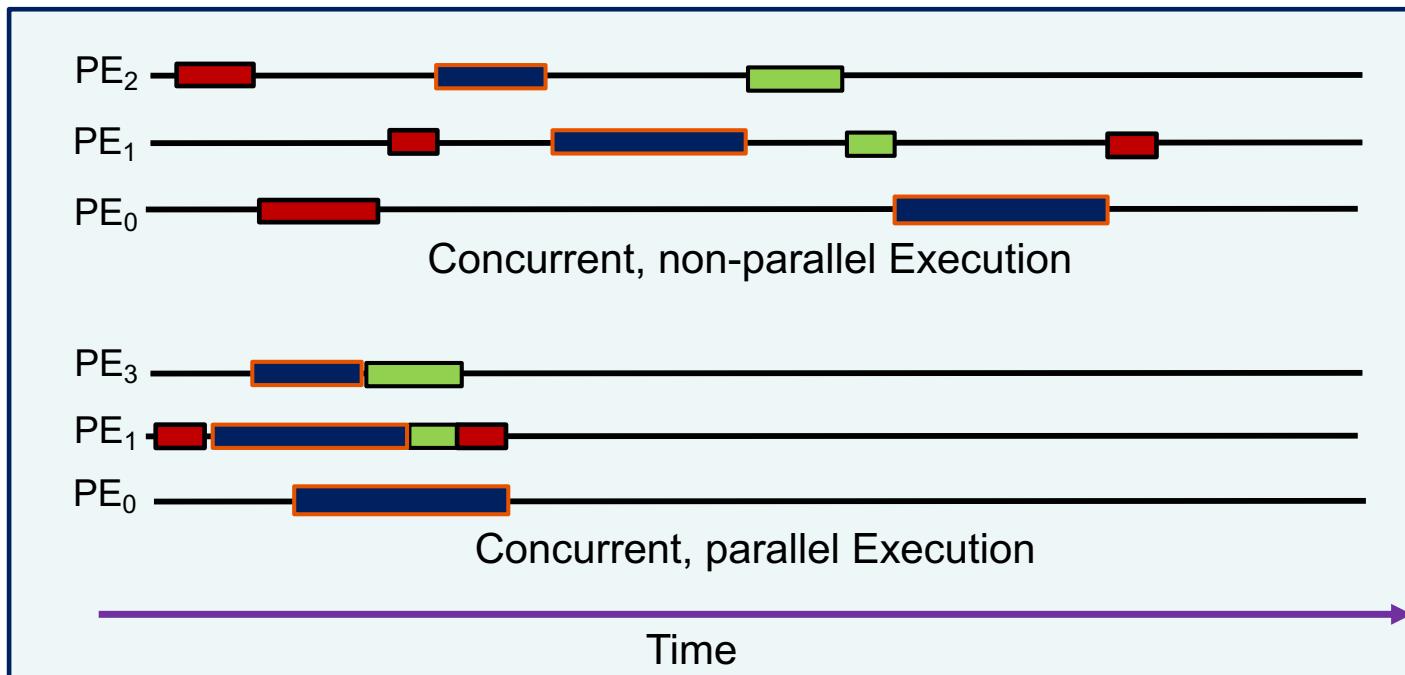
Outline

OpenMP®

- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- Memory Model
- Irregular Parallelism and Tasks
- Recap
- Beyond the Common Core:
 - Worksharing Revisited
 - Additional options for Mutual exclusion
 - Thread Affinity and Data Locality

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**.

Consider two threads: a producer/consumer pair

```
#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;
}
```

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

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.

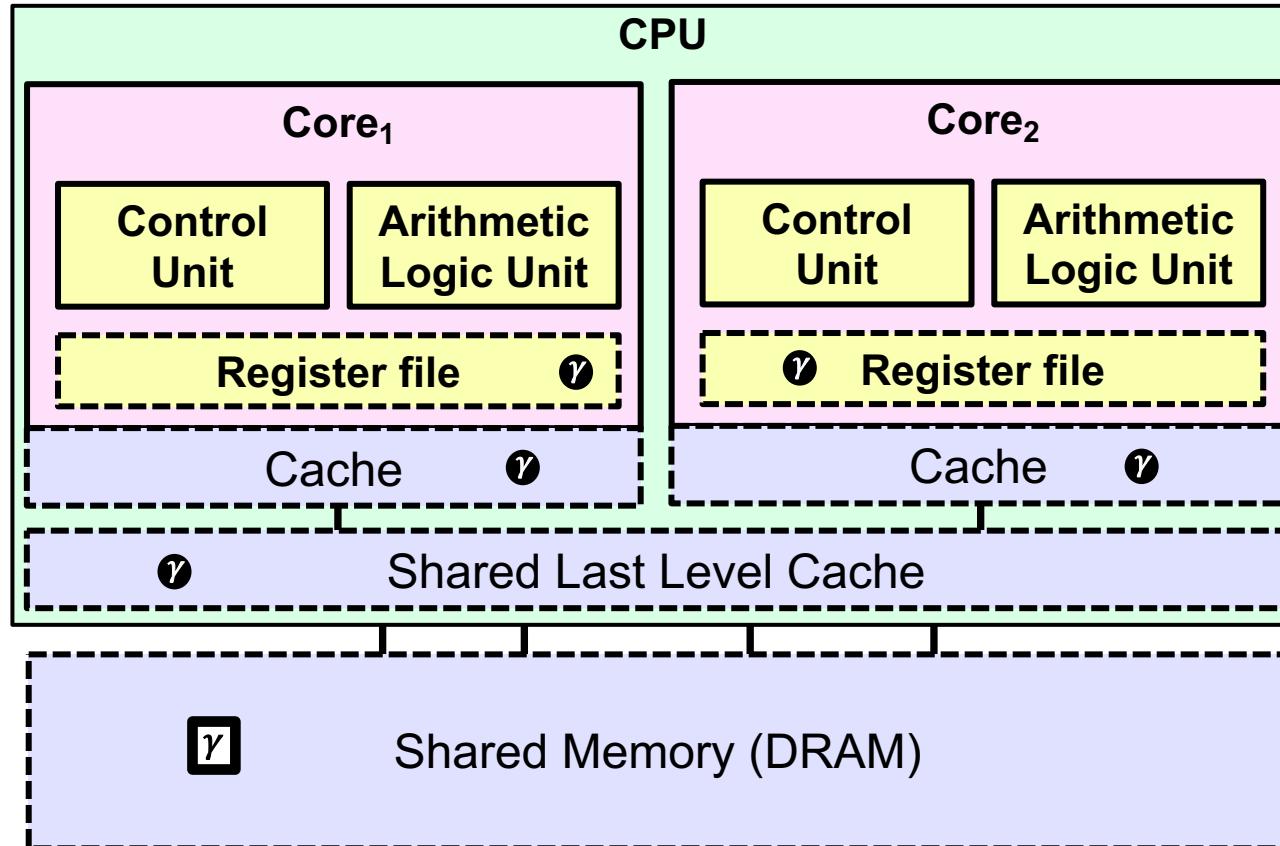
In the jargon of concurrent
programming, this is called
a “spin lock”

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 ...

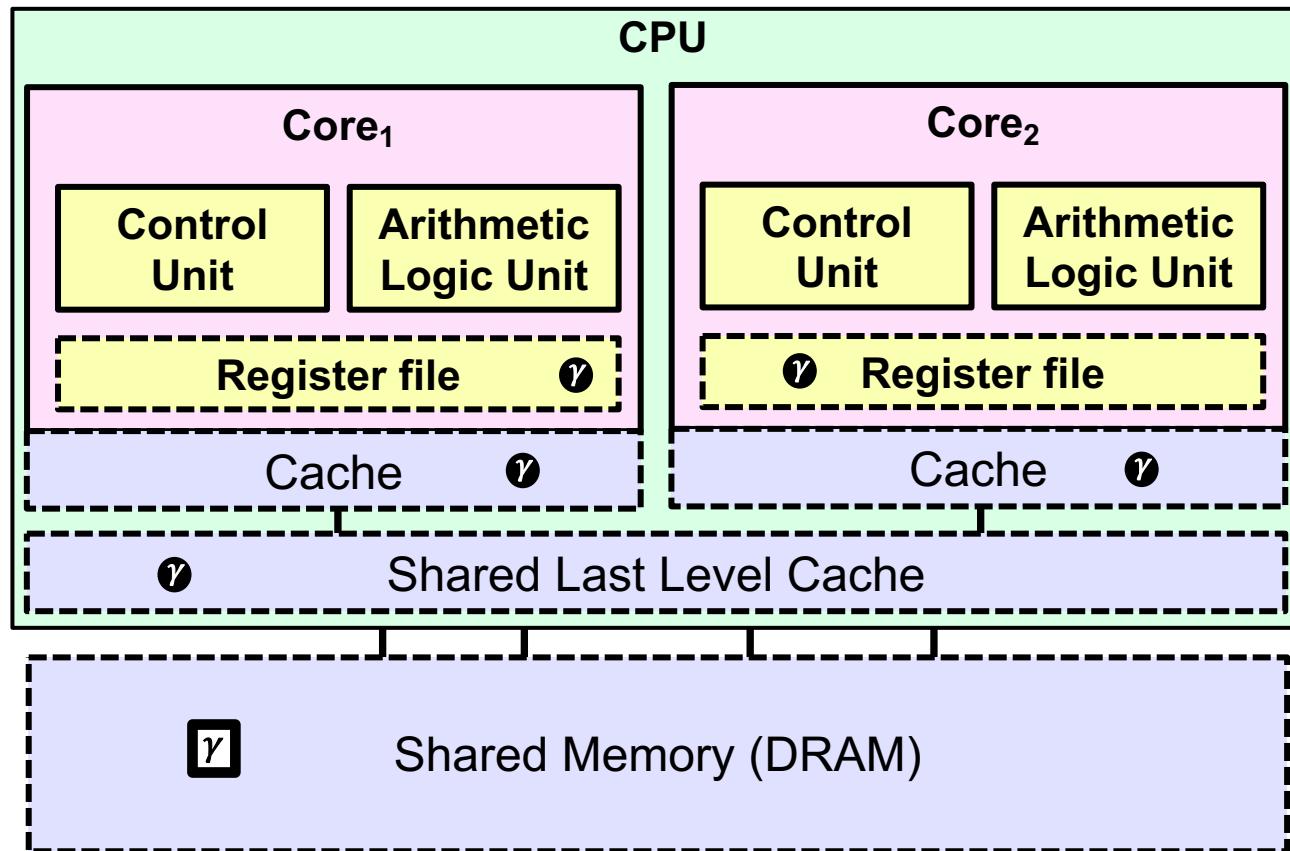
- A shared address space is a region of memory visible to the team of threads ... multiple threads can read and write variables in the shared address space.
- Multiple copies of a variable (such as γ) may be present in memory, at various levels of cache, or in registers and they may ALL have different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



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

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.



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

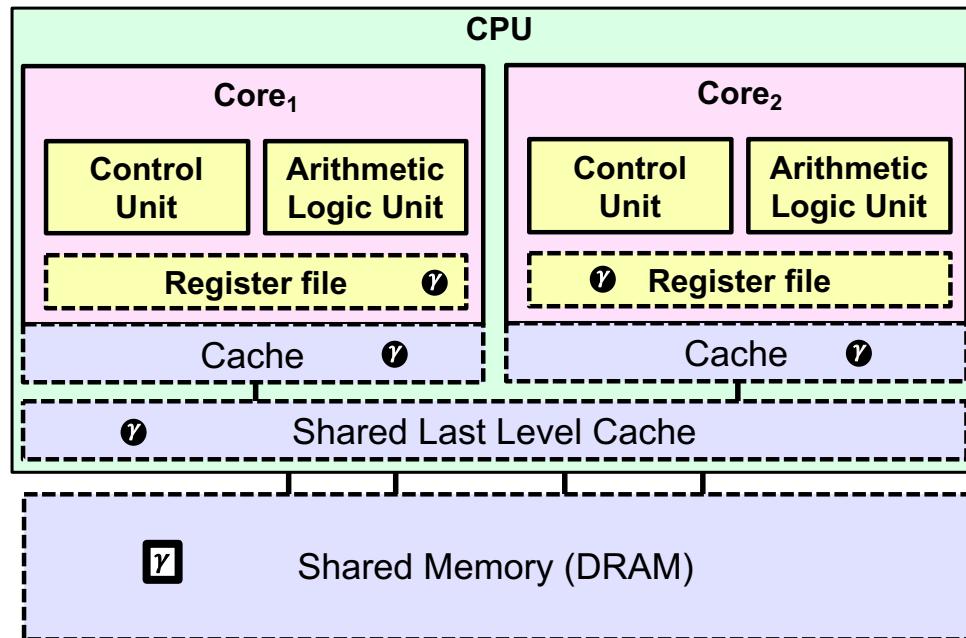
- Which value of γ is the one a thread should see at any point in a computation?

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 **flag** = 1 while **answer** = 0?

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

```
#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

Why did this program fail?

Two issues:

(1) Can **flag** = 1 while **answer** = 0?

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```
#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**

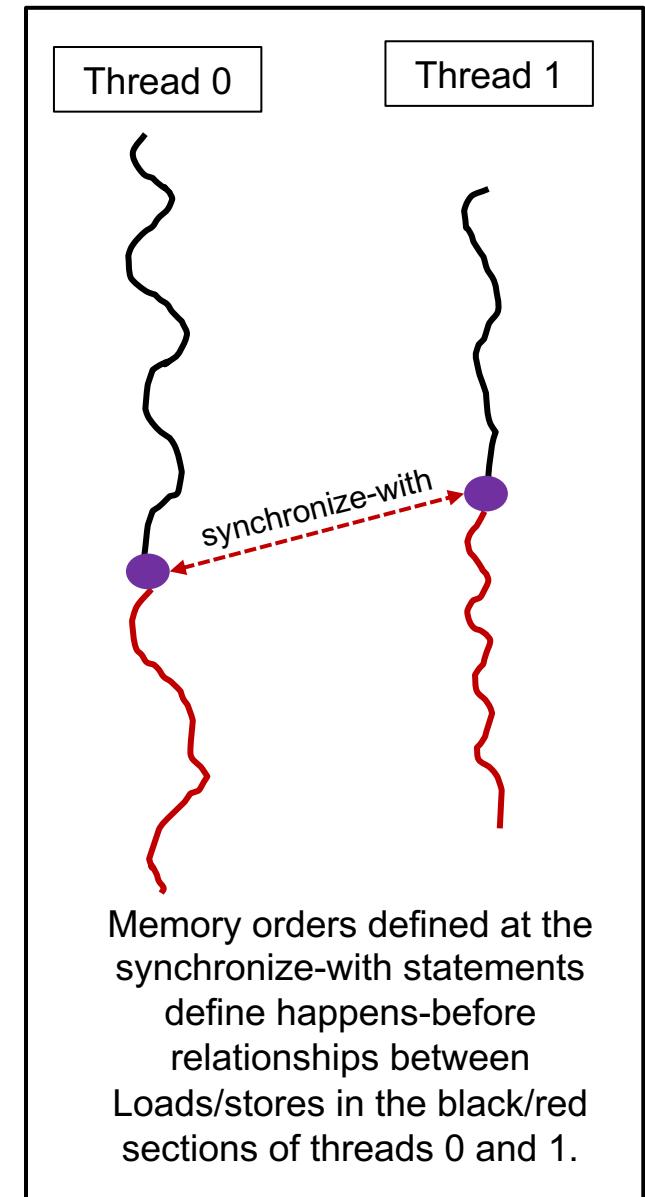
We need to enforce ordering constraints between the concurrent threads ... we need to consider the memory model and put the right synchronization constructs in place.

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.

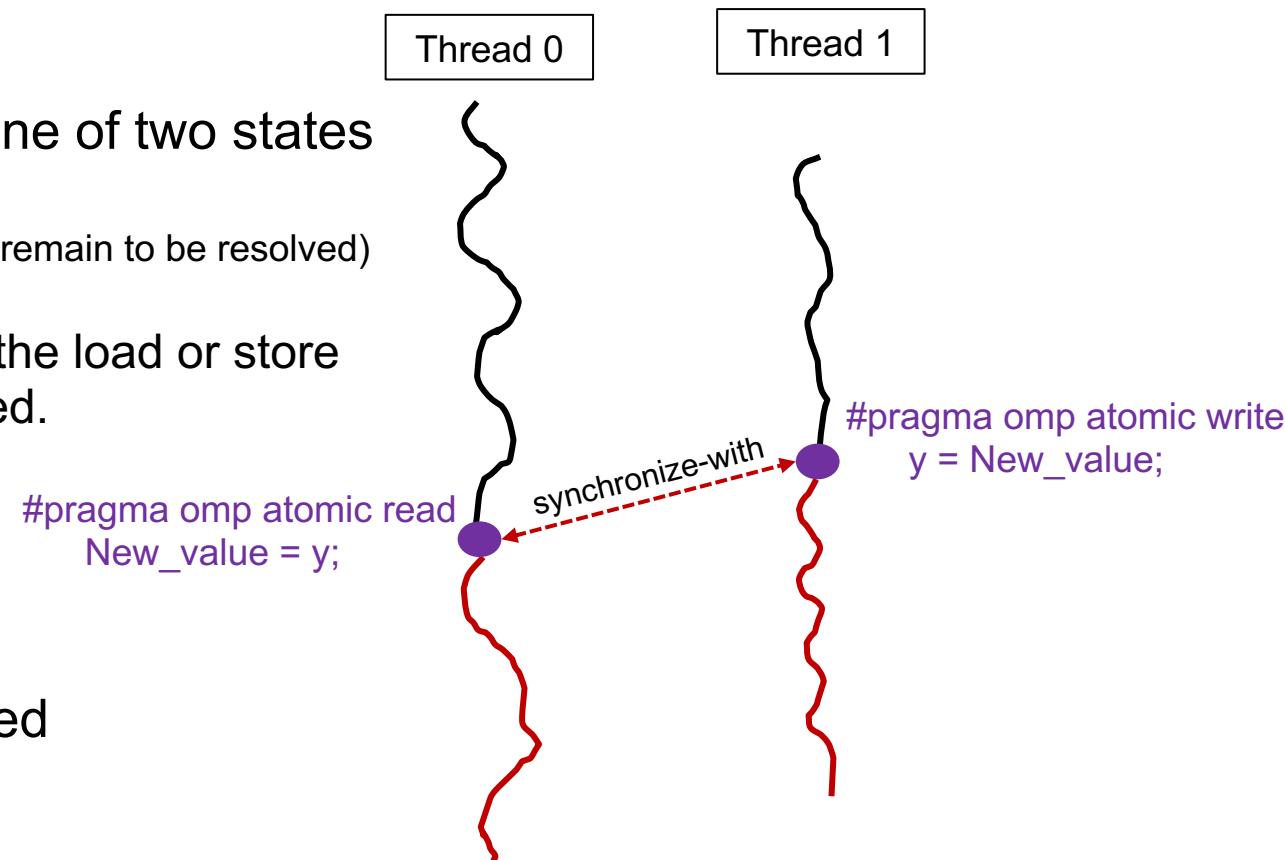


Atomic Operations and Synchronized-with

- 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.

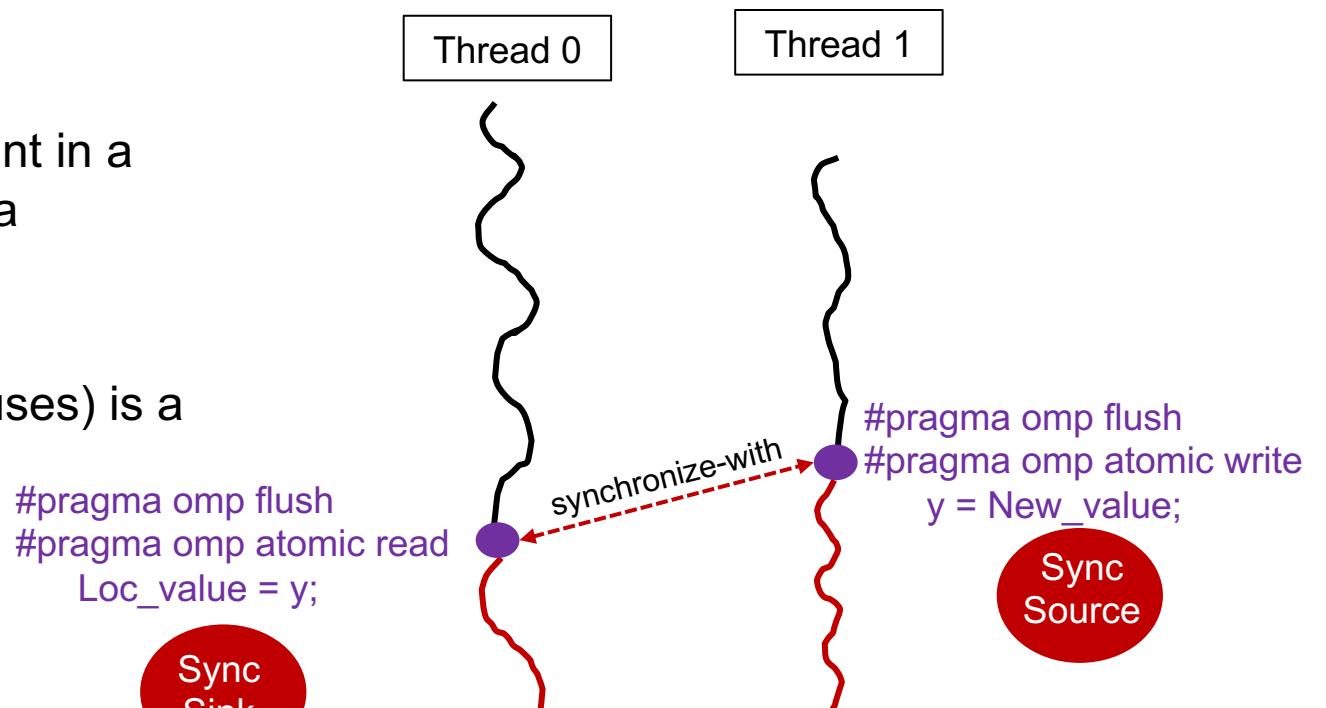
- The key construct is **flush**. ... flush defines a point in a program at which a thread is guaranteed to see a consistent view of memory.

- 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



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.

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

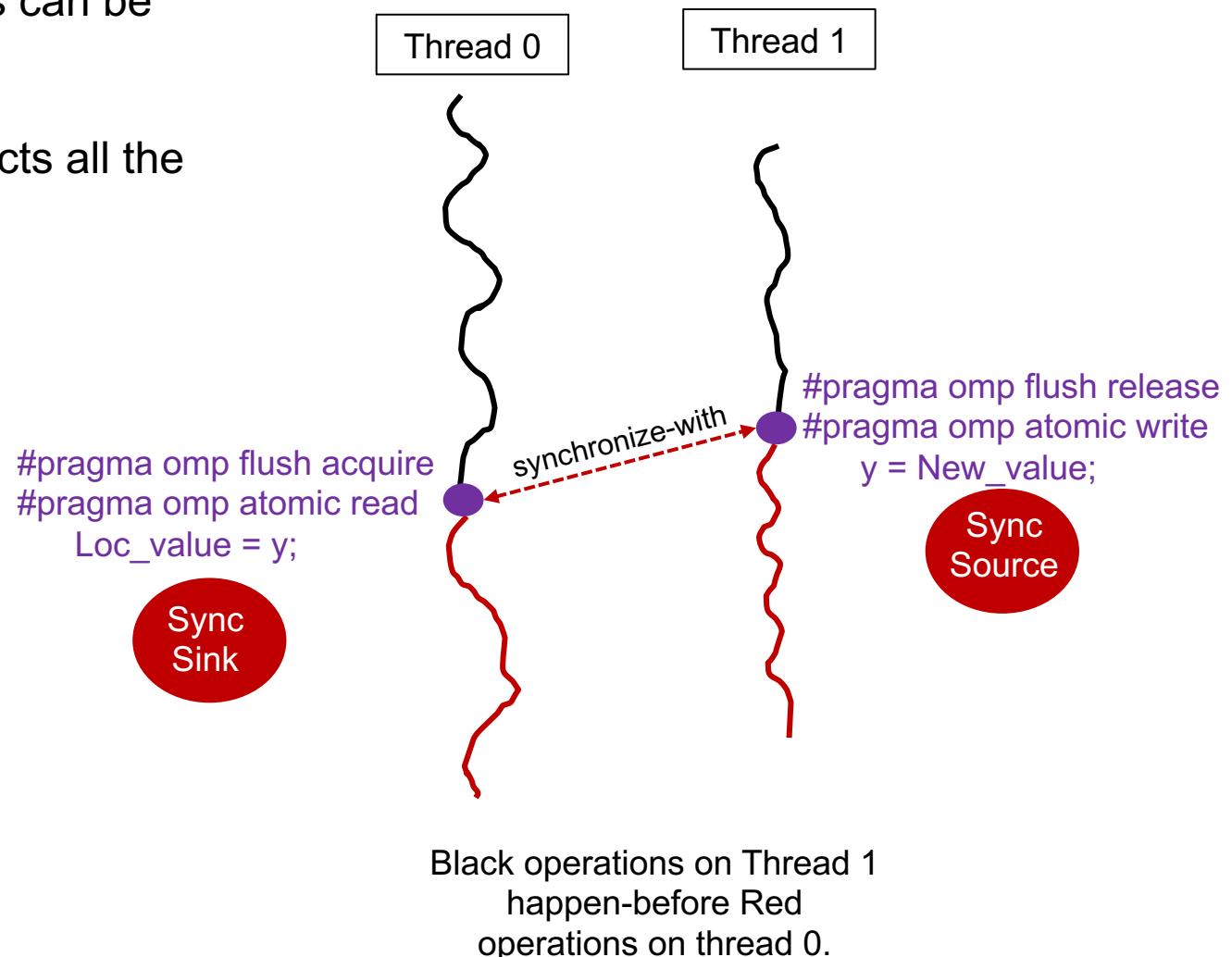
Memory orders

- 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

all memory operations stay above the line
write-release

- Acquire: Reads/writes that follow the read-with-acquire cannot happen-before the read-with-acquire operation.
- Release: Reads/Writes prior to the write-with-release must happen-before the write-with-release.



Memory orders

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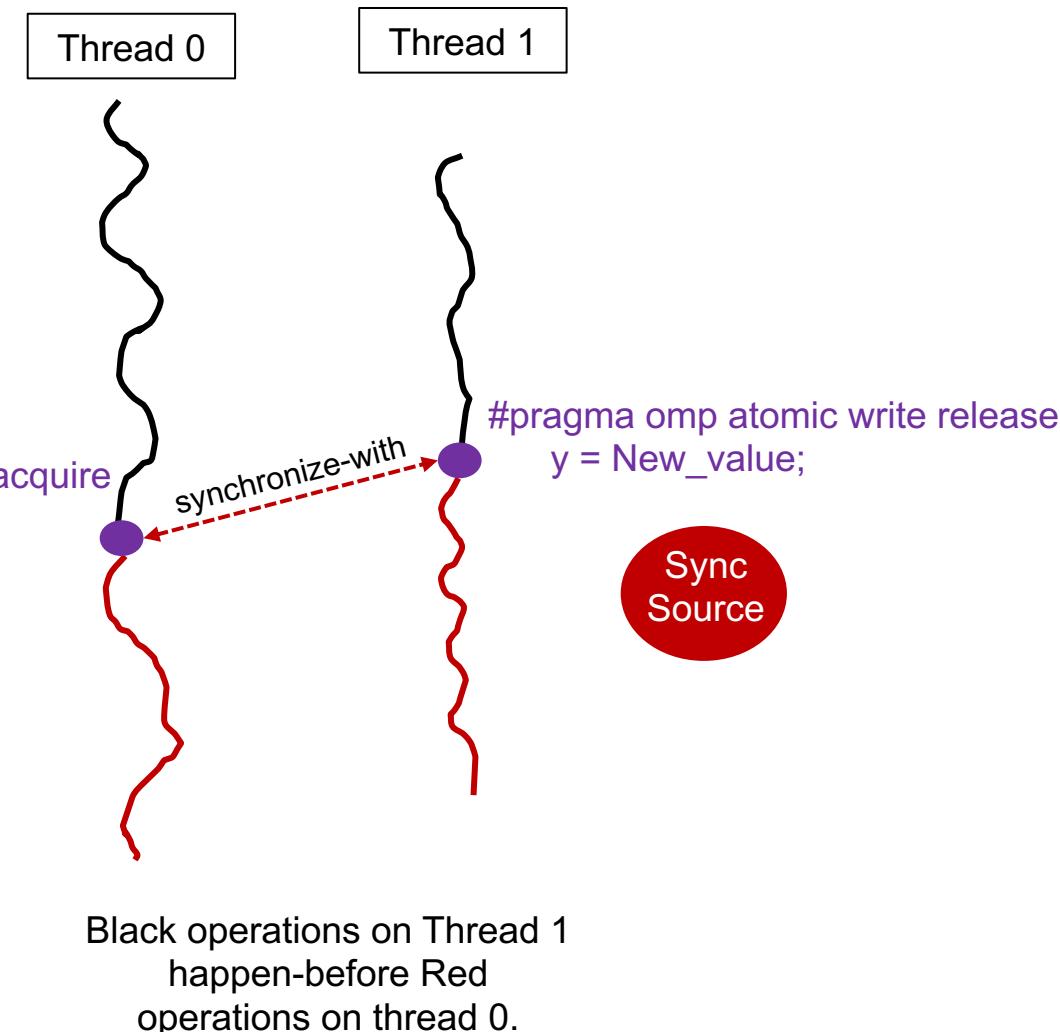
- Acquire: Reads/writes that follow the read-with-acquire cannot happen-before the read-with-acquire operation.
- Release: Reads/Writes prior to the write-with-release must happen-before the write-with-release.

#pragma omp atomic read acquire
Loc_value = y;

Sync Sink

#pragma omp atomic write release
y = New_value;

Sync Source



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 atomic 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;
}
```

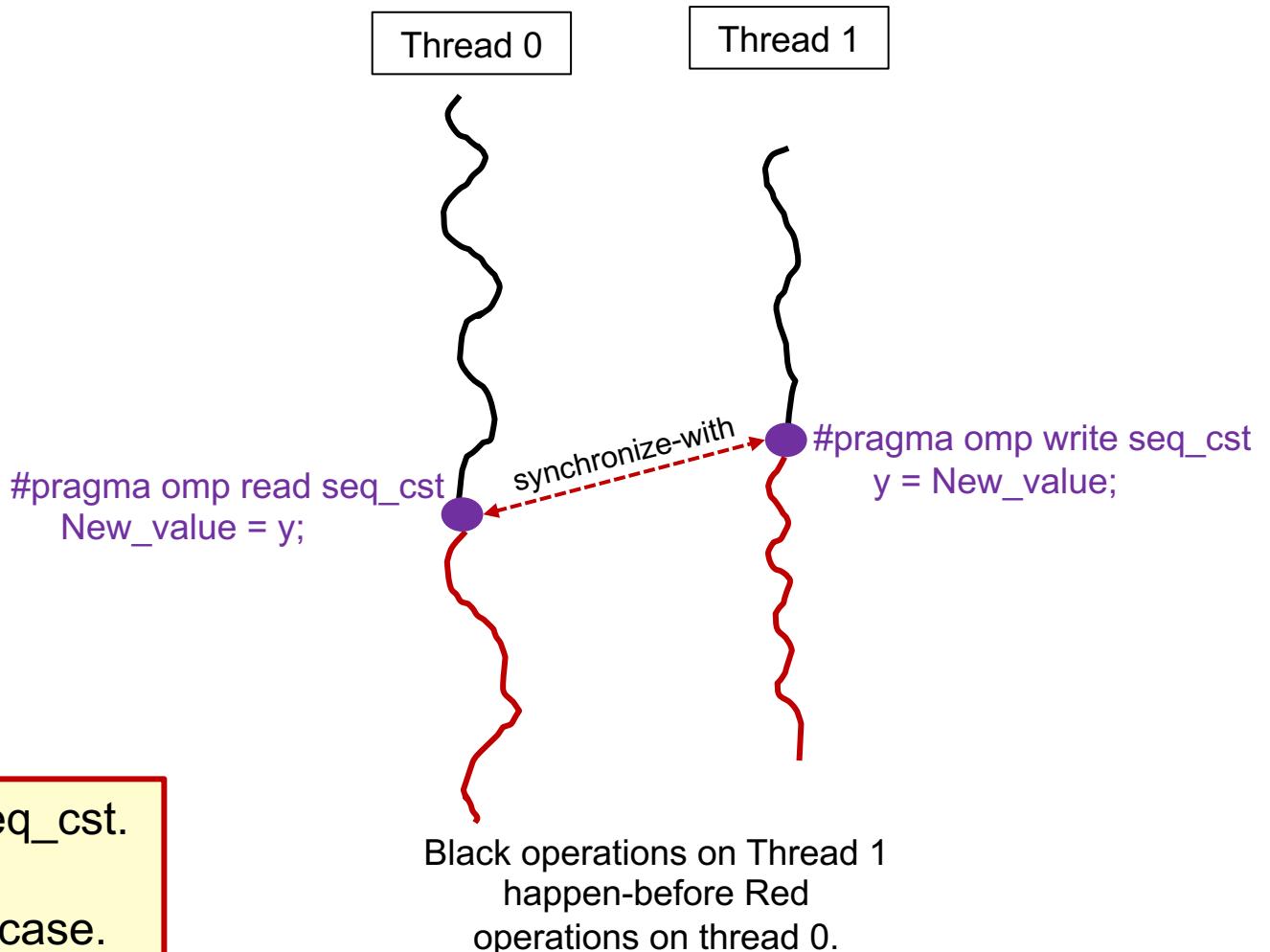
Other Memory orders in OpenMP

- 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

- 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.

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.

- Introduction to OpenMP
- Creating Threads
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- Data Environment
- Memory Model
- • Irregular Parallelism and Tasks
- Recap
- Beyond the Common Core:
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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: My solution

- 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

I am really impressed at how well you all did

- A much more elegant solution several of you came up with Based on the SPMD pattern

```
#pragma omp parallel firstprivate(p)
{
    int id = omp_get_thread_num();
    int nthreads = omp_get_num_threads();
    int count = 0;
    while(p!=NULL && count < id){
        count++;
        p = p->next;
    }
    while (p != NULL) {
        processwork(p);
        int count = 0;
        while(p!=NULL && count < nthreads){
            count++;
            p = p->next;
        }
    }
}
```

Each thread has it's own copy of the list pointer set to the head of the list

Advance the list pointer by a number equal to the thread ID

Increment list pointer by the number of threads

I am really impressed at how well you did

- A particularly elegant, SPMD solution

```
#pragma omp parallel firstprivate(p) default(none)
{
    int i = 0;
    int thread_num = omp_get_thread_num();
    int num_threads = omp_get_num_threads();
    while (p != NULL)
    {
        if(i % num_threads == thread_num)
            processwork(p);
        p = p->next;
        ++i;
    }
}
```

Each thread has it's own copy of the list pointer set to the head of the list

Each of the threads traverses the list, but only one thread processes the work for any given node using the modulus of the count with the number of threads

... and there were other approaches we don't have time to discuss.
A great deal of creativity was displayed in how you all attacked this problem. I am really impressed.

Balancing the load is difficult in this problem

- Notice that the work increases quadratically as you move through the computations of Fibonacci numbers
- A few of you came up with clever methods to overlap computation of the final number (the most expensive by far) by one thread while all the others worked in parallel on the rest.
- One person recognized that this approach meant the code required 2 or more threads.
- That person used an assert() statement to ensure this was the case

```
#include <assert.h>

// And then much later after
// confirming the number of
// threads provided by the system ...

assert (nThrds > 1);
```

This is an excellent programming practice

The best C programmers I know fill their code with assert() statements ... the goal is to write code that is “self debugging” and anticipates and responds to known error scenarios

- If I ran the program with a single thread, I got the following output.

```
Assertion failed: (nThrds > 1), function main, file
Davide_linked.c, line 98.
zsh: abort      ./a.out
```

Linked Lists with OpenMP

```

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]);
}

```

```

#pragma omp parallel firstprivate(p) default(none)
{
    int i = 0;
    int thread_num = omp_get_thread_num();
    int num_threads = omp_get_num_threads();
    while (p != NULL)
    {
        if(i % num_threads == thread_num)
            processwork(p);
        p = p->next;
        ++i;
    }
}

```

```

#pragma omp parallel firstprivate(p)
{
    int id = omp_get_thread_num();
    int nthreads = omp_get_num_threads();
    int count = 0;
    while(p!=NULL && count < id){
        count++;
        p = p->next;
    }
    while (p != NULL) {
        processwork(p);
        int count = 0;
        while(p!=NULL && count < nthreads){
            count++;
            p = p->next;
        }
    }
}

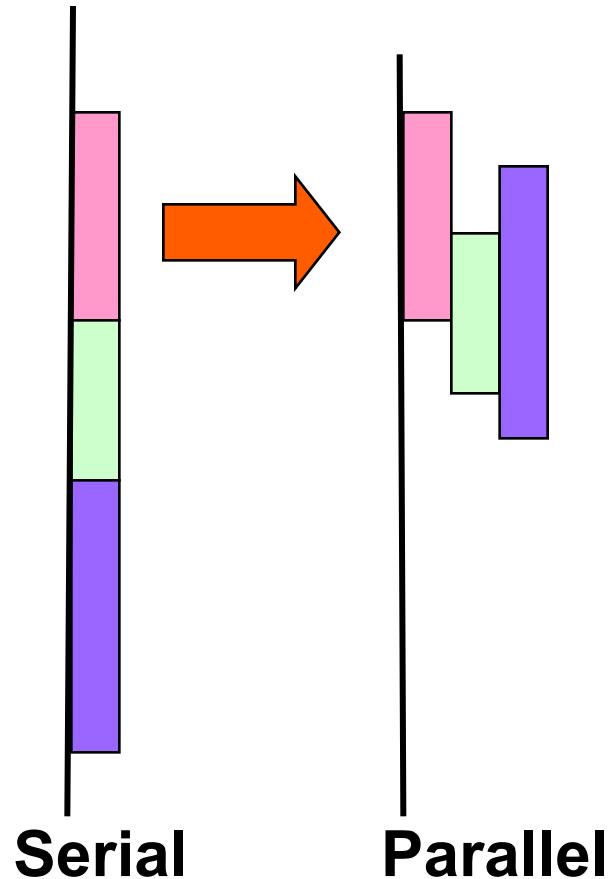
```

With so much code to add and multiple passes through the data, all of these approaches are kind of ugly.

There has got to be a better way to handle irregular problems

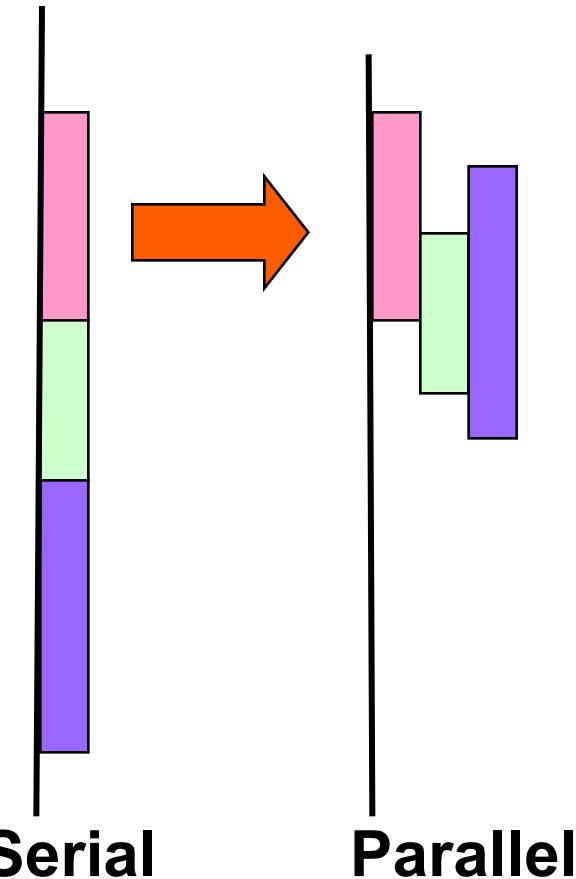
What are Tasks?

- 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 ← Create some threads
{
```

```
    #pragma omp single ← One Thread
    {                                packages tasks
```

```
        #pragma omp task
            fred();
```

```
        #pragma omp task
            daisy();
```

```
        #pragma omp task
            billy();
```

```
}
```

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
```

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

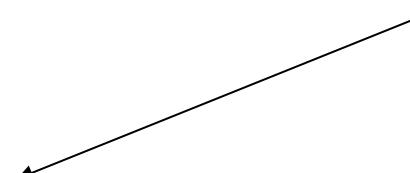
- Variables can be shared, private or firstprivate with respect to task
- These concepts are a little bit different compared with threads:
 - If a variable is **shared** on a task construct, the references to it inside the construct are to the storage with that name at the point where the task was encountered
 - 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;

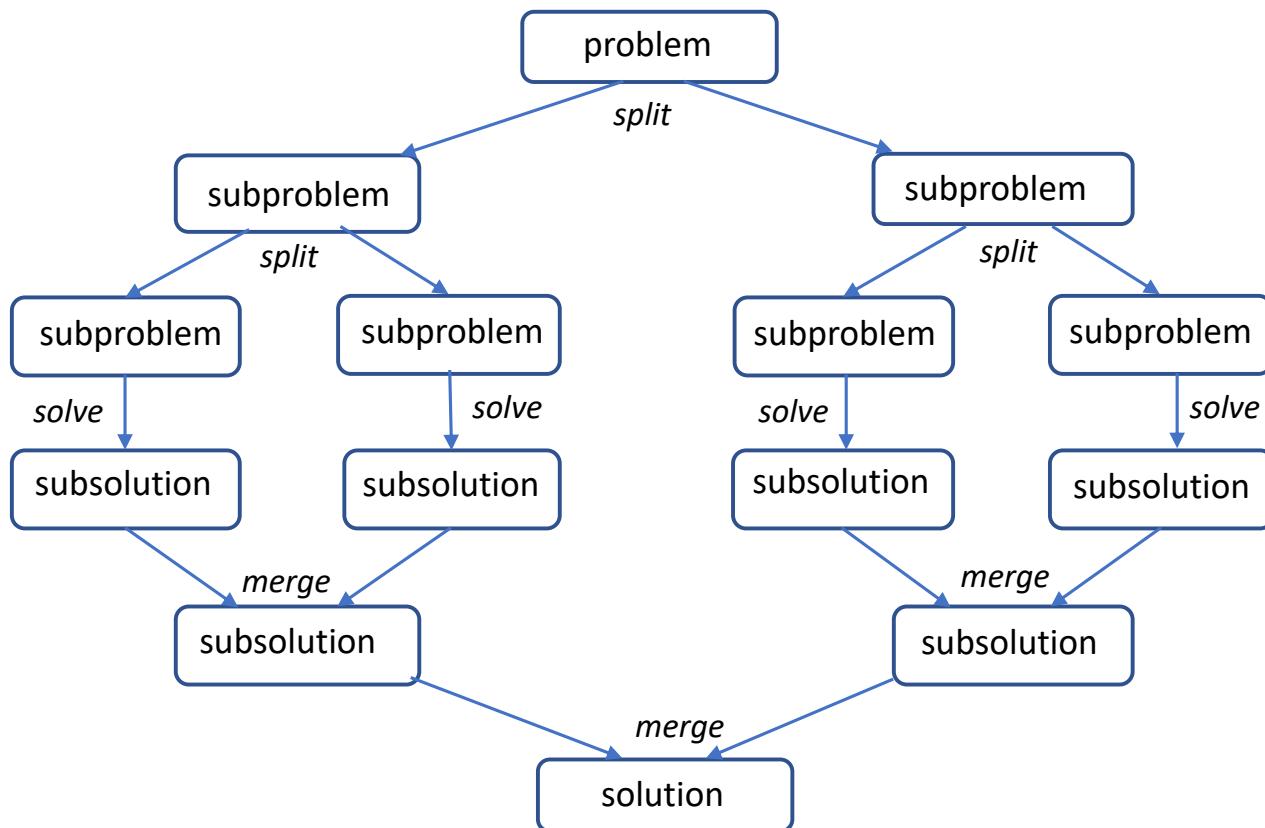
#pragma omp task shared(x)
    x = fib(n-1);
#pragma omp task shared(y)
    y = fib (n-2);
#pragma omp taskwait
    return (x+y);
}

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?**

Results*: Pi with tasks

threads	1 st 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

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 - Worksharing Revisited
 - Additional options for Mutual exclusion
 - Thread Affinity and Data Locality

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.

There is Much More to OpenMP than the Common Core

- Synchronization mechanisms
 - locks, synchronizing flushes and several forms of atomic
- Data environment
 - lastprivate, threadprivate, default(private|shared)
- Fine grained task control
 - dependencies, tied vs. untied tasks, task groups, task loops ...
- Vectorization constructs
 - simd, uniform, simdlen, inbranch vs. nobranch,
- Map work onto an attached device (such as a GPU)
 - target, teams distribute parallel for, target data ...
- ... and much more. The OpenMP 5.0 specification is over 618 pages!!!

Don't become overwhelmed. Master the common core and move on to other constructs when you encounter problems that require them.

OpenMP Organizations

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

www.openmp.org

- OpenMP User’s Group (cOMPunity) URL:

www.community.org

Get involved, join the ARB and cOMPunity.

Help define the future of OpenMP

Resources

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

The screenshot shows the OpenMP website's "Specifications" page. At the top, the "Specifications" menu item is highlighted in orange. Below the navigation bar, the page title "Specifications" is displayed in large white text on a teal background. In the top right corner of the main content area, there is a breadcrumb trail: "Home > Specifications". The main content area contains two cards: one for the "OpenMP 5.2 Specification" and another for the "OpenMP 5.1 Specification". Each card features a document icon, the specification name, and a bulleted list of related links. A callout bubble from the bottom left points to the "OpenMP API 5.2 Examples" link in the 5.2 specification card.

The OpenMP API specification for parallel programming

Home Specifications Community ▾ Resources ▾ News & Events ▾ About ▾

Specifications

Home > Specifications

OpenMP 5.2 Specification

- OpenMP API 5.2 Specification – Nov 2021
 - Softcover Book on Amazon
- OpenMP API Additional Definitions 2.0 – Nov 2020
- OpenMP API 5.2 Reference Guide (English) (Japanese)
- OpenMP API 5.2 Supplementary Source Code
- OpenMP API 5.2 Examples – April 2022
 - Softcover Book on Amazon
- OpenMP API 5.2 Stack Overflow

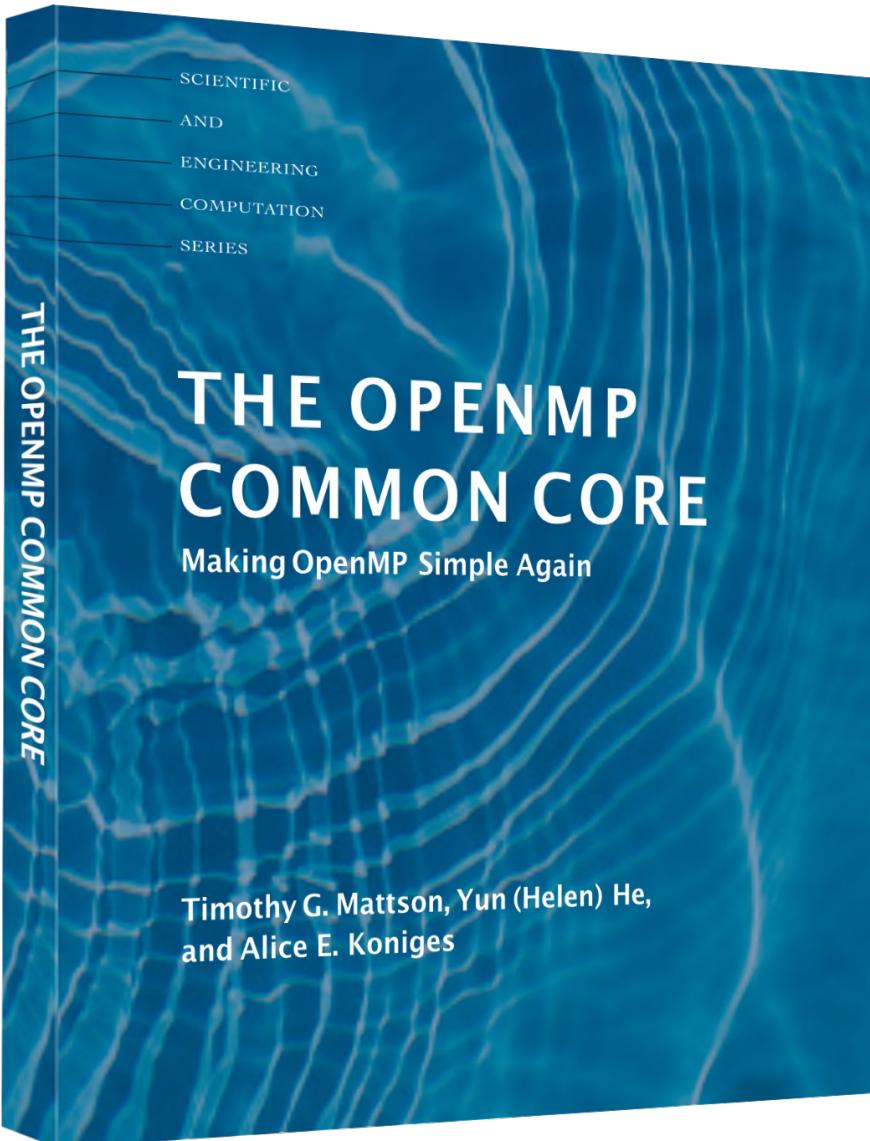
OpenMP 5.1 Specification

- OpenMP API 5.1 Specification – Nov 2020
 - HTML Version
 - Softcover Book on Amazon
- OpenMP API Additional Definitions 2.0 – Nov 2020
- OpenMP API 5.1 Reference Guide
- OpenMP API 5.1 Supplementary Source Code
- OpenMP API 5.1 Examples – August 2021
- OpenMP API 5.1 Stack Overflow

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

To learn OpenMP:

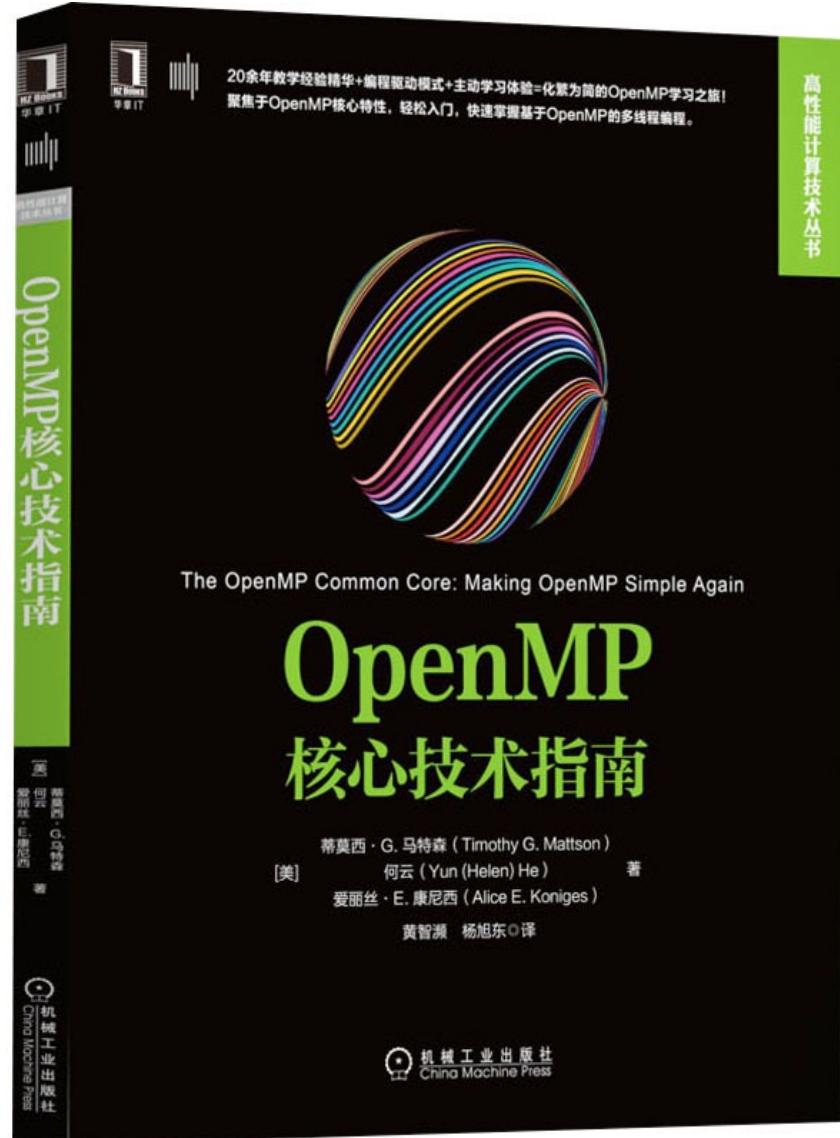
- An exciting new book that Covers the Common Core of OpenMP plus a few key features beyond the common core that people frequently use
- It's geared towards people learning OpenMP, but as one commentator put it ... **everyone at any skill level should read the memory model chapters.**
- Available from MIT Press



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

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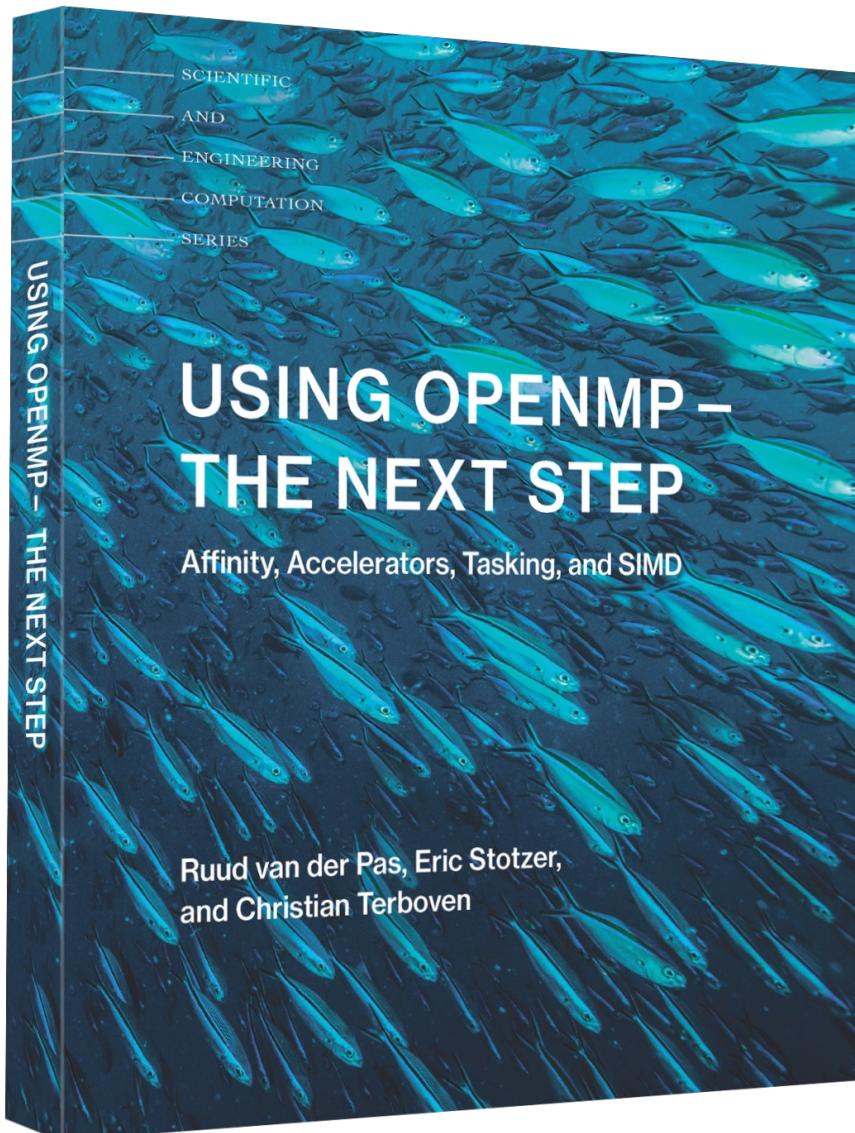


And now in Chinese

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

Books about OpenMP

A great book that covers
OpenMP features beyond
OpenMP 2.5

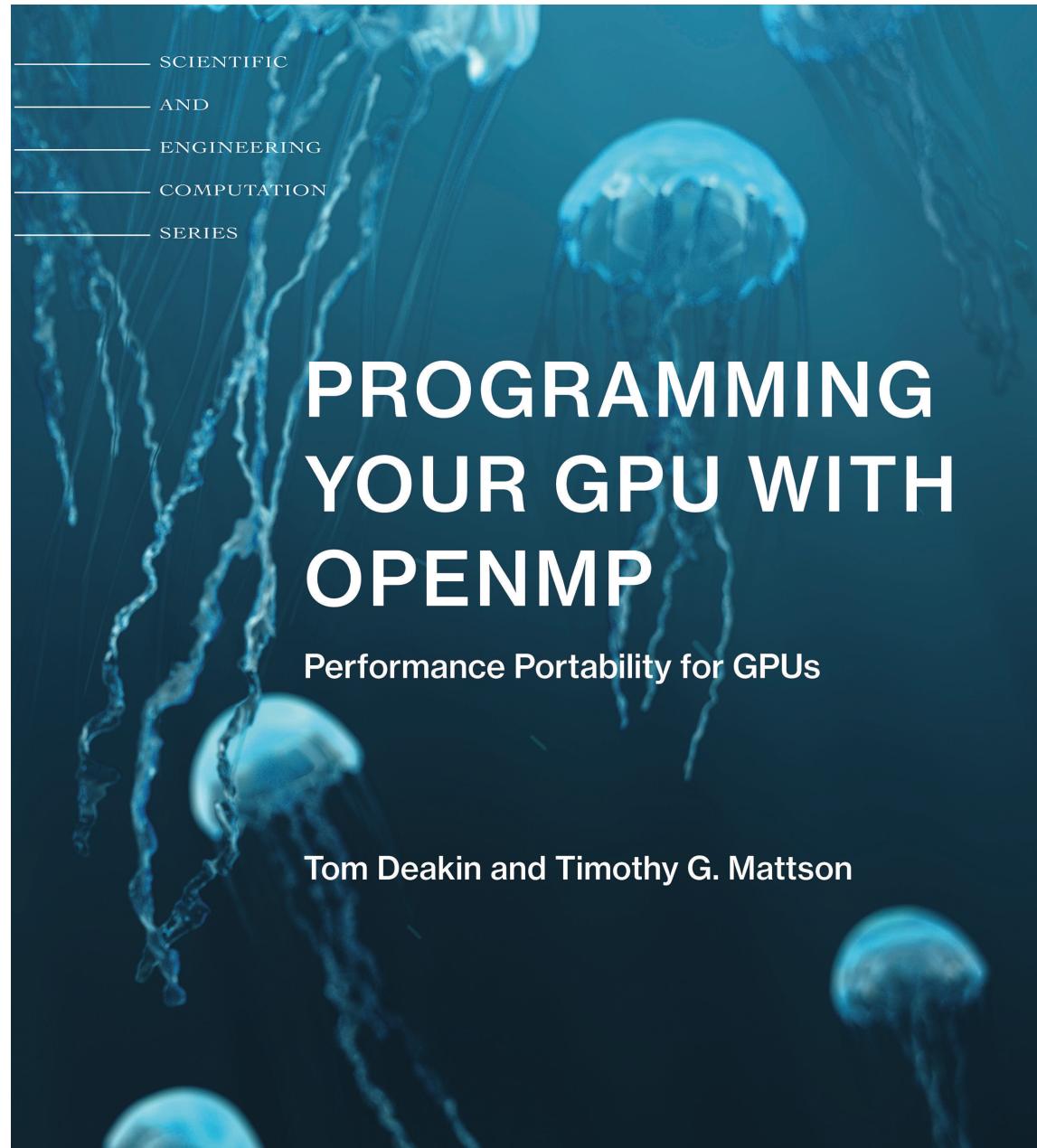


Books about OpenMP

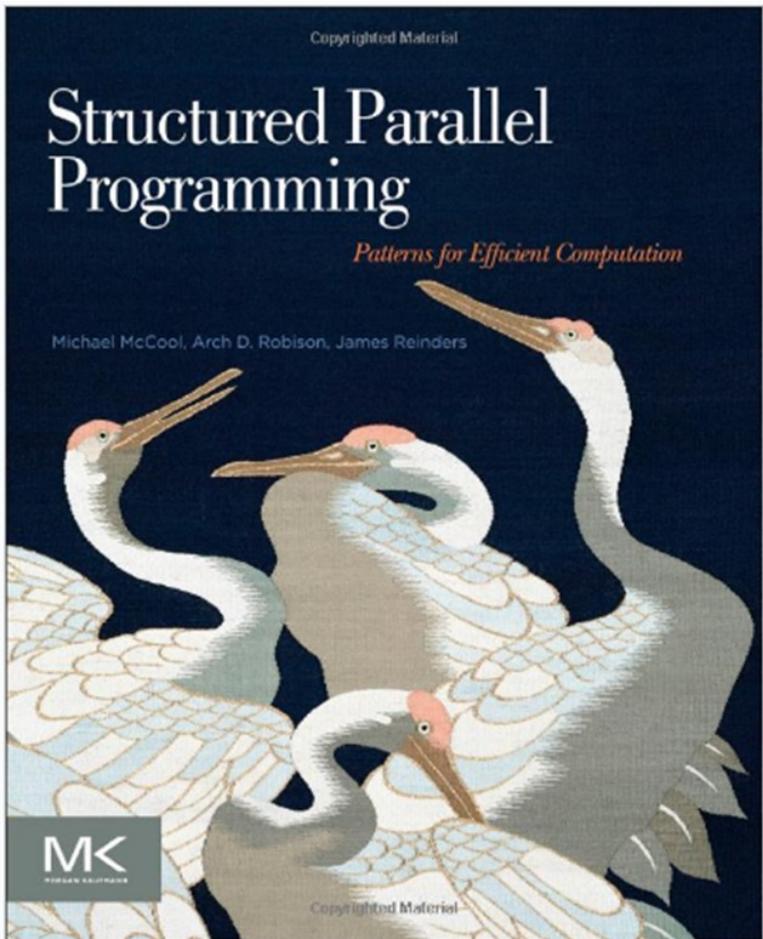
The latest book on OpenMP ...

Comes out in early November 2023.

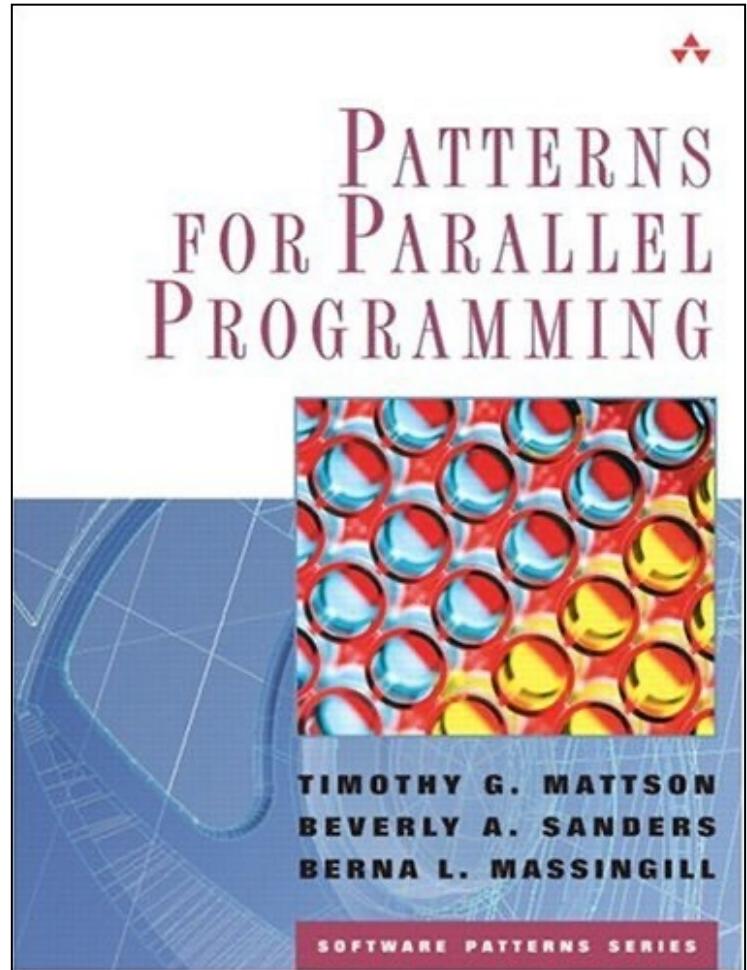
A book about how to use OpenMP to program a GPU.



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

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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, nonmonotonic and simd.

Loop Worksharing Constructs: The schedule clause

Schedule Clause	When To Use	
STATIC	Pre-determined and predictable by the programmer	Least work at runtime : scheduling done at compile-time
DYNAMIC	Unpredictable, highly variable work per iteration	Most work at runtime : complex scheduling logic used at run-time
GUIDED	Special case of dynamic to reduce scheduling overhead	
AUTO	When the runtime can “learn” from previous executions of the same loop	

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;
```

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

```
#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;
```

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

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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

- 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()`

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

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);
```

One lock per case ... even and odd

```
#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);  
}
```

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

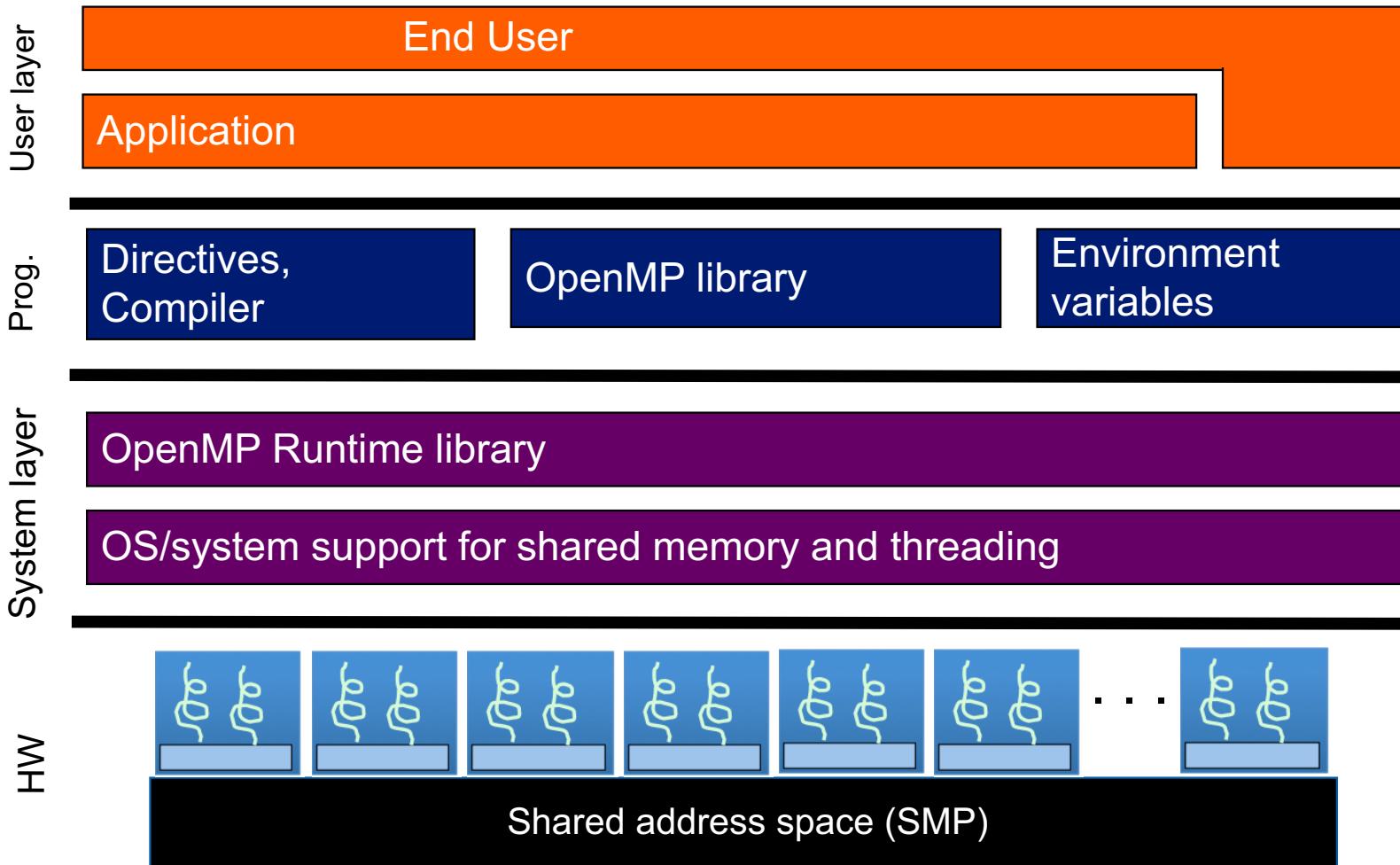
Free-up storage when done.

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 two different ways.** Try to minimize the time to generate the histogram.
- Time ONLY the assignment to the histogram. Can you beat the sequential time?

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OpenMP basic definitions: Basic Solution stack



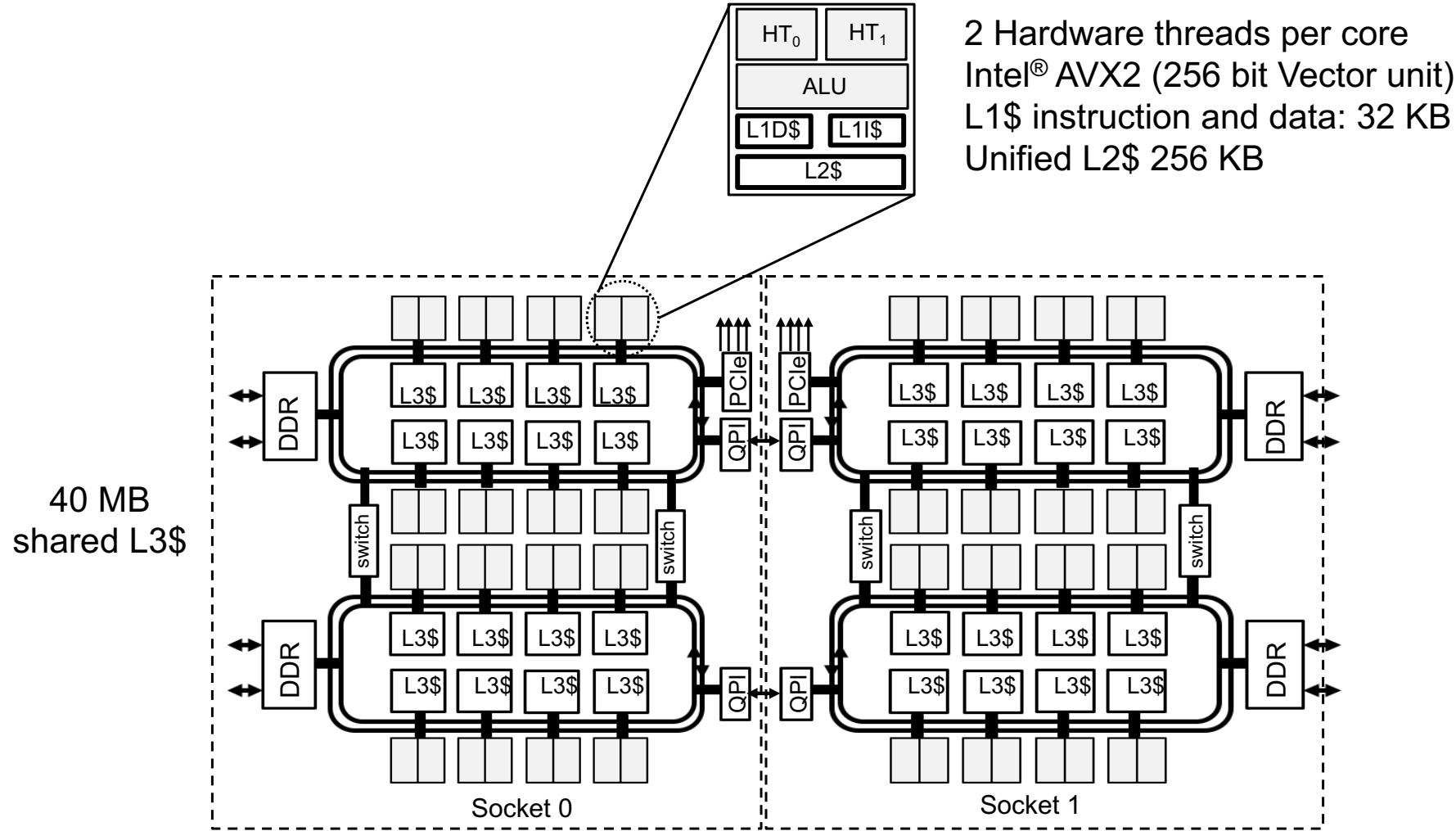
In learning OpenMP, you consider a Symmetric Multiprocessor (SMP)
i.e. lots of threads with "**equal cost access**" to memory

CPU Architecture Trend

- Multi-socket nodes with rapidly increasing core counts
 - Memory per core decreases
 - Memory bandwidth per core decreases
 - Network bandwidth per core decreases
- Applications often use a hybrid programming model with three levels of parallelism
 - MPI between nodes or sockets
 - Shared memory (such as OpenMP) on the nodes/sockets
 - Increase vectorization for lower level loop structures

A Typical CPU Node in an HPC System

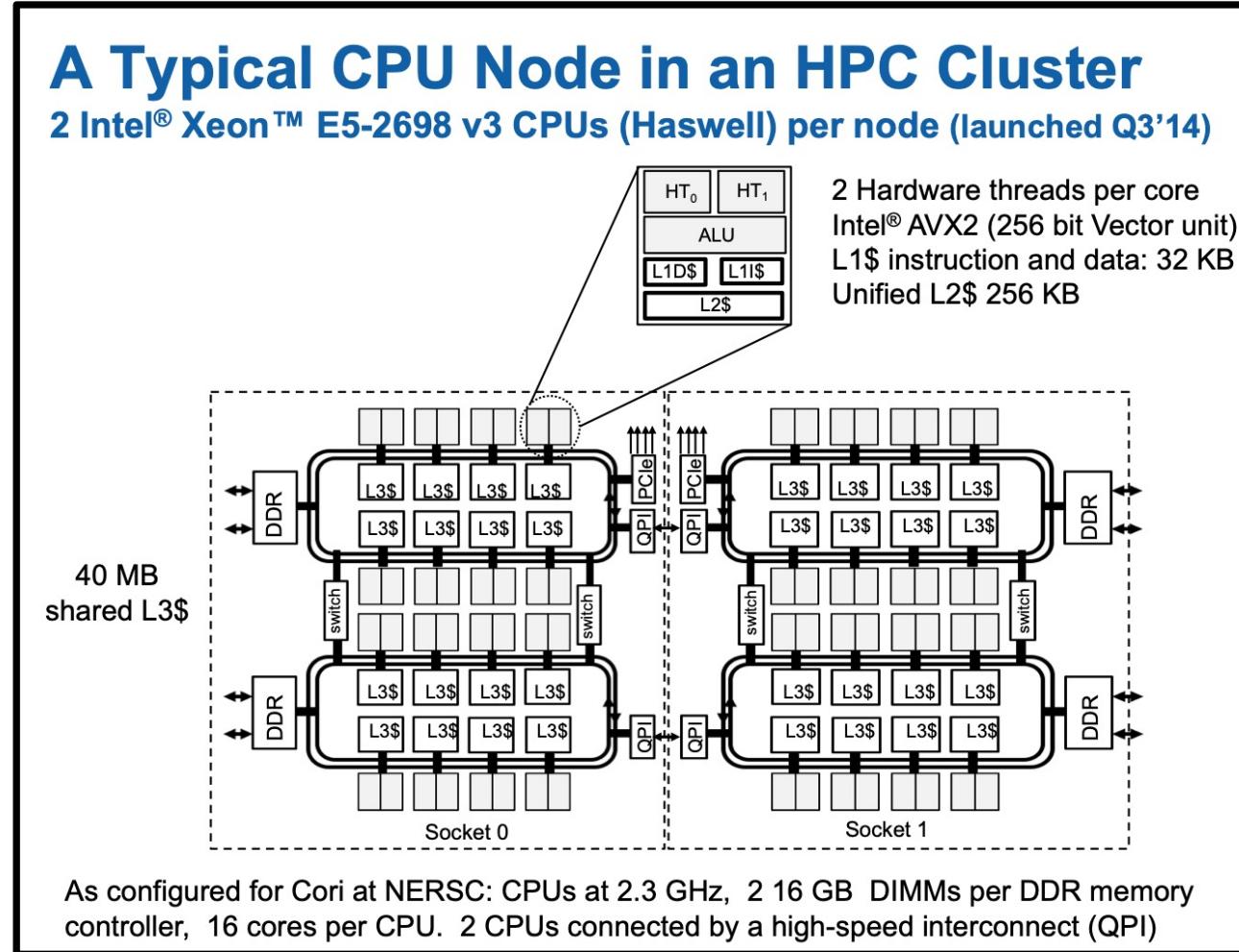
2 Intel® Xeon™ E5-2698 v3 CPUs (Haswell) per node (launched Q3'14)



As configured for Cori at NERSC: CPUs at 2.3 GHz, 2 16 GB DIMMs per DDR memory controller, 16 cores per CPU. 2 CPUs connected by a high-speed interconnect (QPI)

Does this look like an SMP node to you?

There may be a single address space, but there are multiple levels of non-uniformity to the memory. This is a **Non-Uniform Memory Architecture** (NUMA)



Even a single CPU is properly considered a NUMA architecture

NUMA Systems

- Most systems today are Non-Uniform Memory Access (NUMA)
- Accessing memory in remote NUMA is slower than accessing memory in local NUMA
- Accessing High Bandwidth Memory is faster than DDR

A Generic Contemporary NUMA System

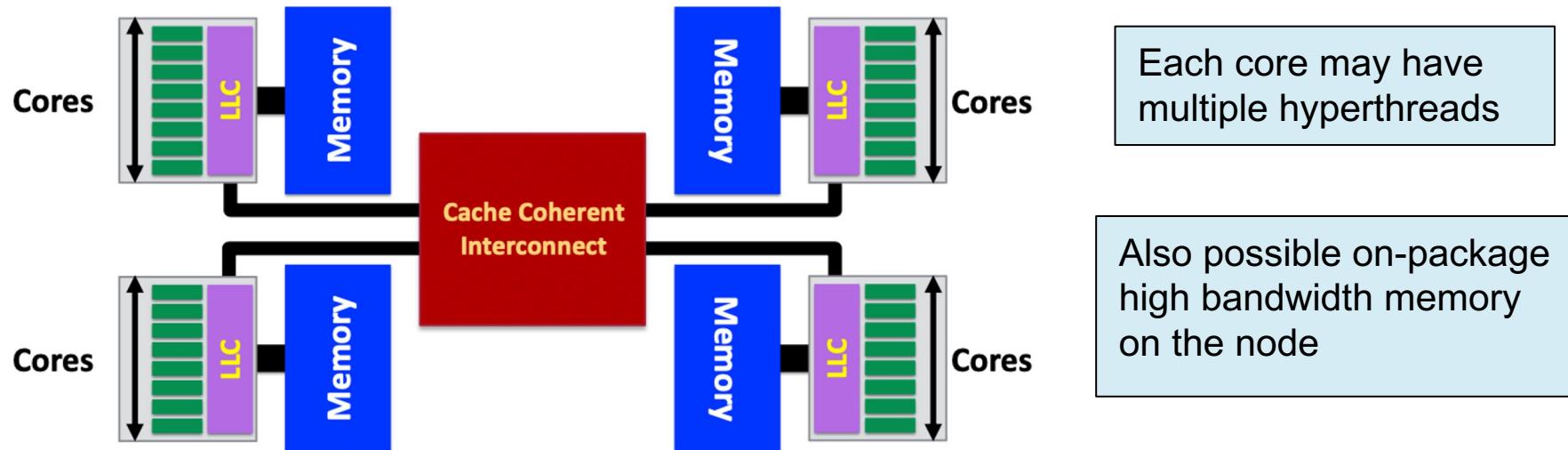


Diagram courtesy Ruud van der Pas

Memory Locality

- Most systems today are Non-Uniform Memory Access (NUMA)
- Example, the Intel® Xeon Phi™ processor

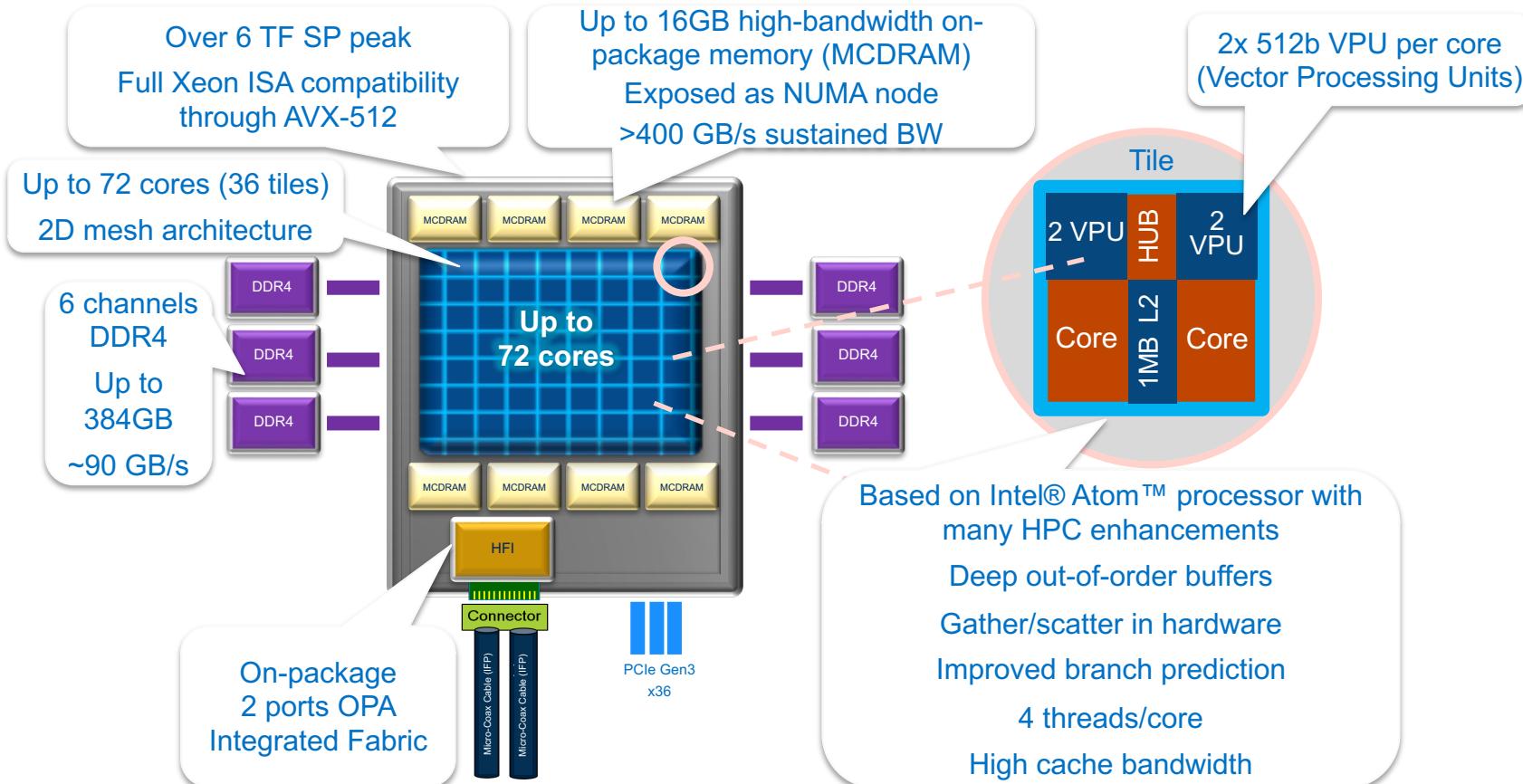


Diagram is for conceptual purposes only and only illustrates a CPU and memory – it is not to scale and does not include all functional areas of the CPU, nor does it represent actual component layout.

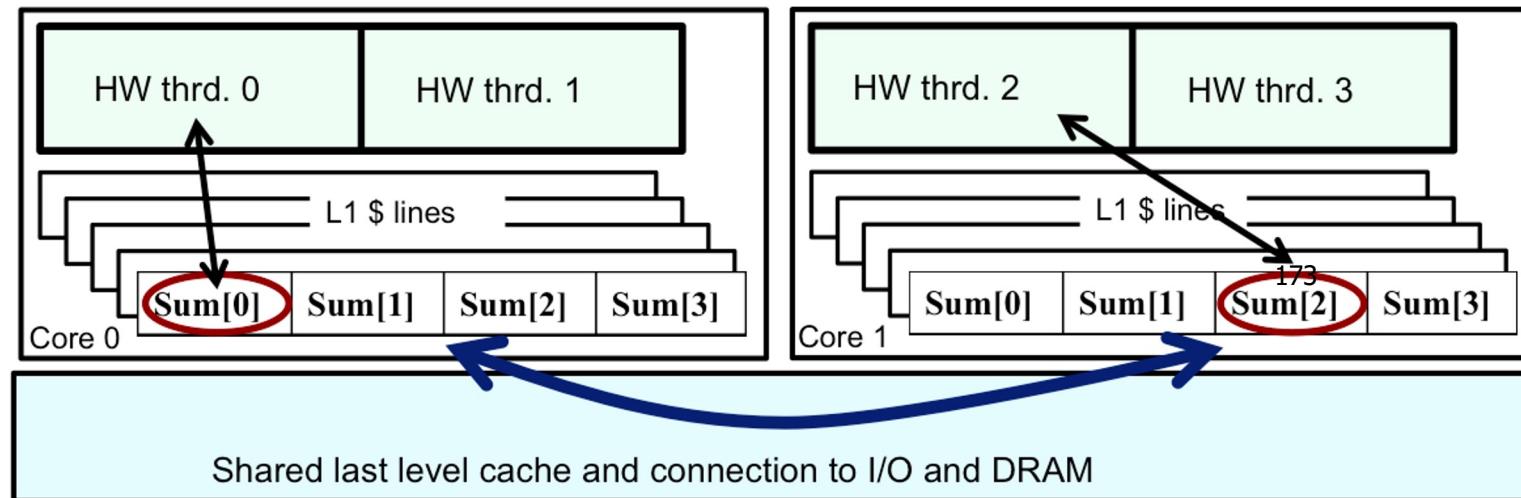
Memory Locality

- Memory access in different NUMA domains are different
 - Accessing memory in remote NUMA is slower than accessing memory in local NUMA
 - Accessing High Bandwidth Memory on KNL* is faster than DDR
- OpenMP does not explicitly map data across shared memories
- Memory locality is important since it impacts both memory and intra-node performance

*KNL: Intel® Xeon Phi™ processor 7250 with 68 cores @ 1.4 Ghz ...
the “bootable” version that sits in a socket, not a co-processor

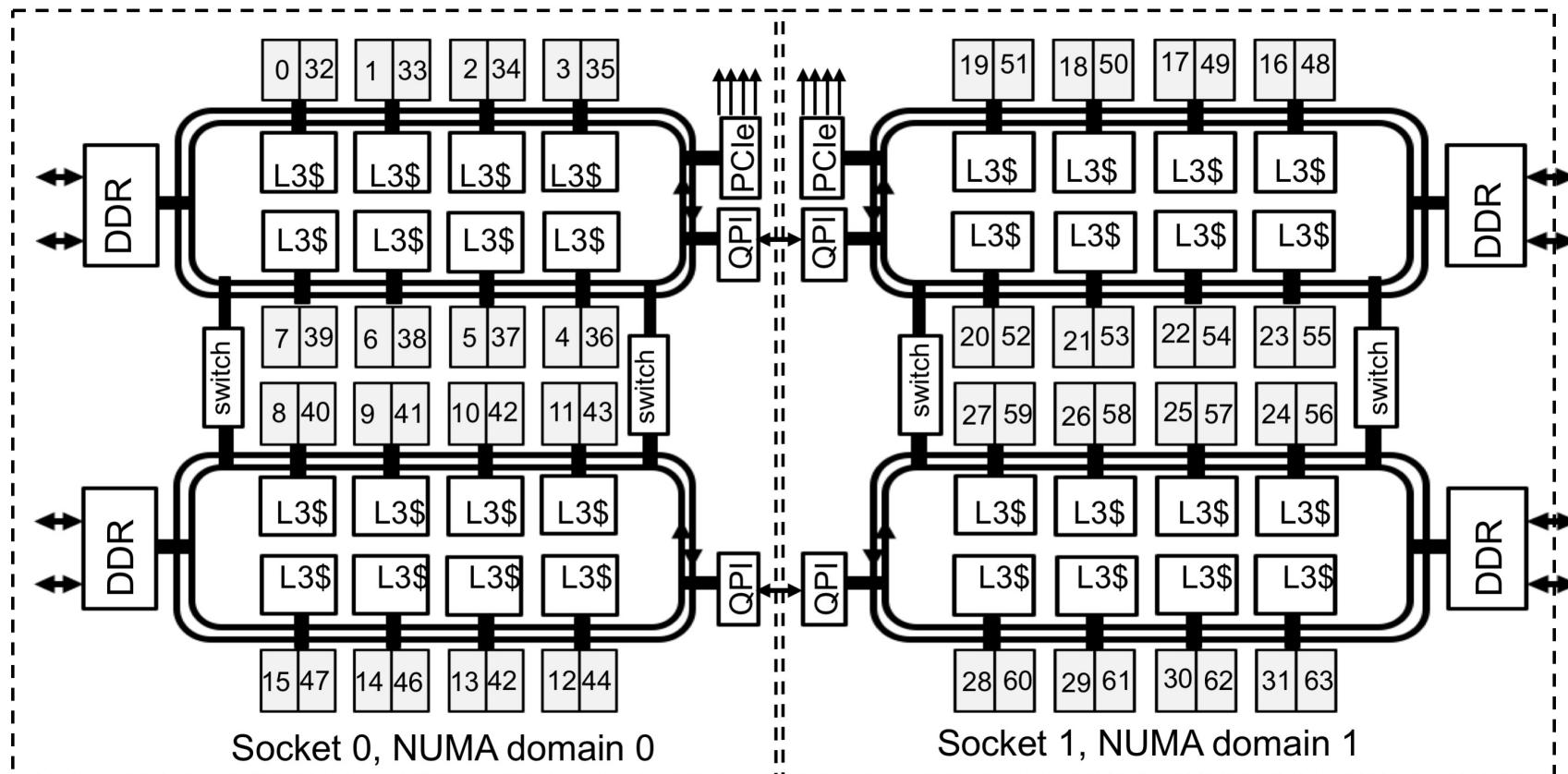
Cache Coherence and False Sharing

- ccNUMA node: cache-coherence NUMA node.
- Data from memory are accessed via cache lines.
- Multiple threads hold local copies of the same (global) data in their caches. Cache coherence ensures the local copy to be consistent with the global data.
- Main copy needs to be updated when a thread writes to local copy.
- Writes to same cache line from different threads is called false sharing or cache thrashing, since it needs to be done in serial. Use atomic or critical or private variables to avoid race condition.



Exploring your NUMA world: numactl

- numactl shows you how the OS processor-numbers map onto the physical cores of the chip:



2 Intel® Xeon™ E5-2698 v3 CPUs (Haswell) per node (launched Q3'14)

Tool to Check NUMA Node Information: numactl

- **numactl**: controls NUMA policy for processes or shared memory
 - **numactl -H**: provides NUMA info of the CPUs

**Haswell node example
32 cores, 2 sockets**

```
% numactl -H
available: 2 nodes (0-1)
node 0 cpus: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47
node 0 size: 64430 MB
node 0 free: 63002 MB
node 1 cpus: 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 48 49 50 51 52 53 54 55 56 57 58 59 60 61
62 63
node 1 size: 64635 MB
node 1 free: 63395 MB
node distances:
node  0  1
 0: 10 21 } ←
 1: 21 10 }
```

Shows relative costs In this case, there's a factor of two in the cost of the local (on CPU) DRAM vs going to the other socket

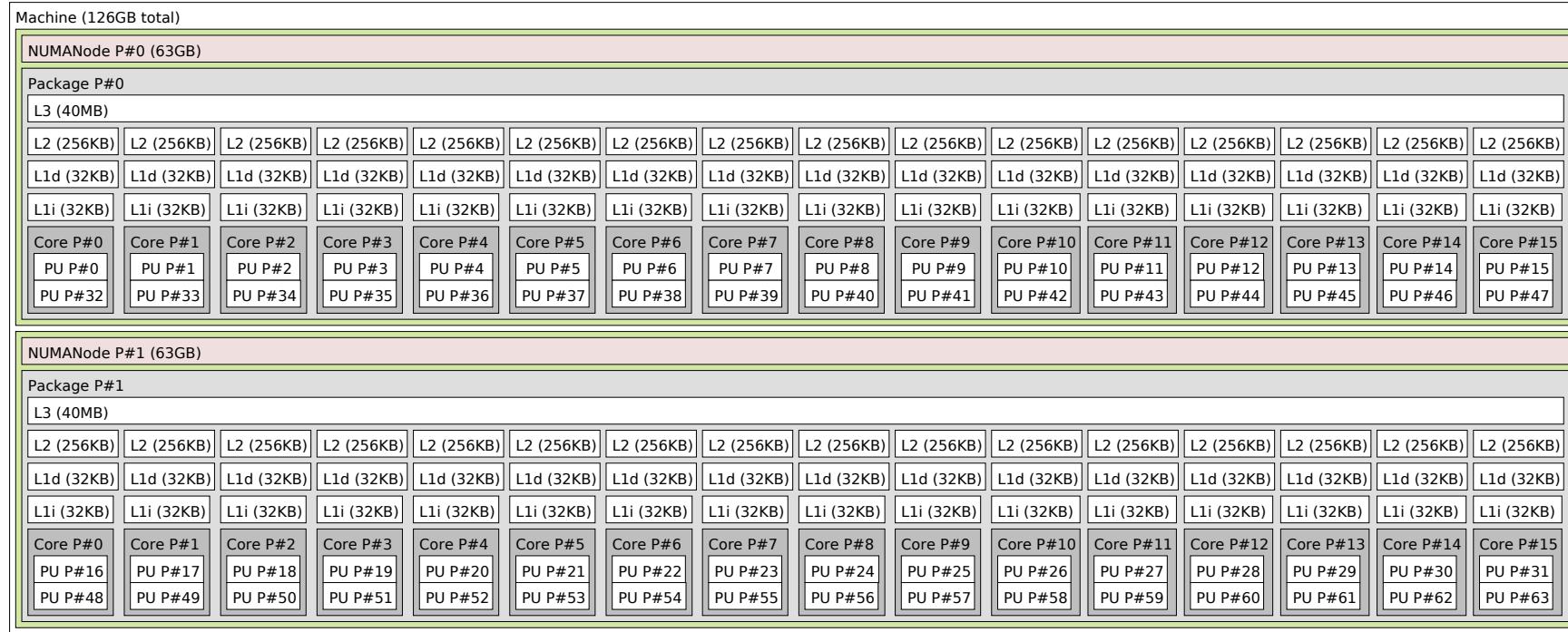
*Haswell: 16-core Intel® Xeon™ Processor E5-2698 v3 at 2.3 GHz

Use numactl Command Line Tool

- **numactl** is a Linux tool to investigate and handle NUMA
- Can be used to request CPU or memory binding
 - Use “**numactl <options> ./myapp**” as the executable (instead of “**./myapp**”)
- CPU binding example:
 - **% numactl --cpunodebind 0,1 ./code.exe**
only use cores of NUMA nodes 0 and 1
- Memory binding example:
 - **% numactl --membind 1 ./code.exe**
only use memory in NUMA nodes 1, such as the MCDRAM (High Bandwidth Memory) in KNL quad, flat mode

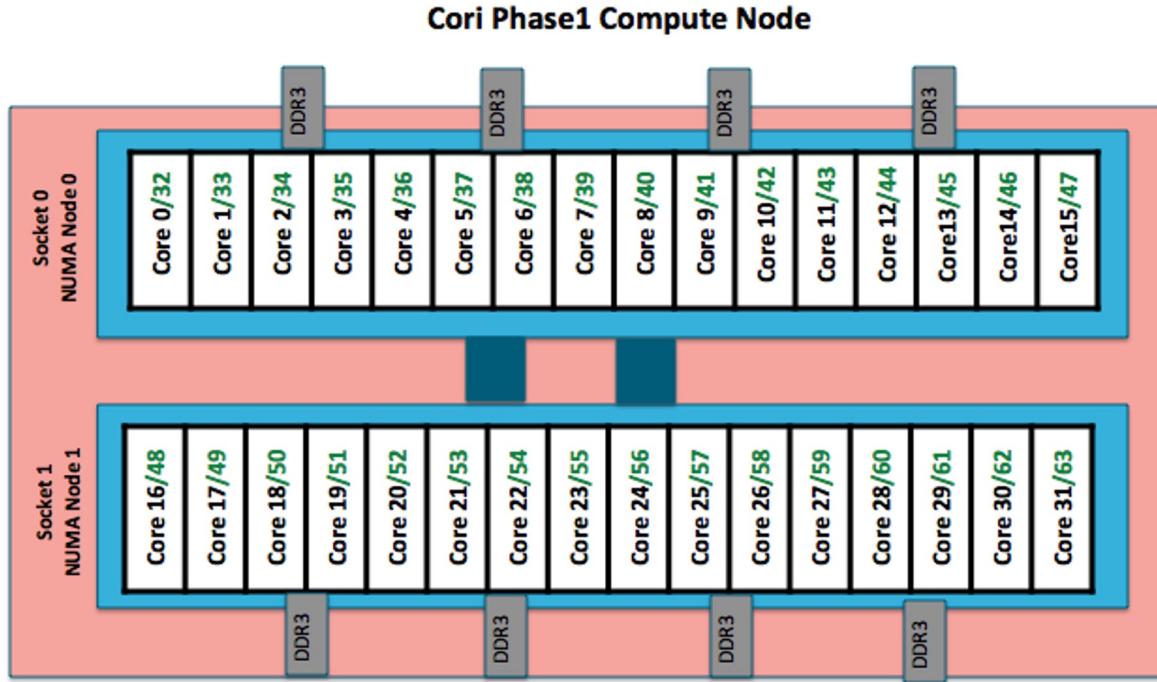
Tools to Check Node Information: hwloc

- Portable Hardware Locality (hwloc)
 - `hwloc-ls` and `lstopo`: provides a **text** and **graphical** representation of the system topology, NUMA nodes, cache info, and the mapping of procs.



**Haswell node example
32 cores, 2 sockets**

Haswell Compute Nodes Example



To obtain processor info:

Get on a compute node:

```
% salloc -N 1 -C ...
```

Then:

```
% numactl -H
```

```
or % cat /proc/cpuinfo
```

```
or % hwloc-ls
```

- Each Haswell node has 2 Intel Xeon 16-core Haswell processors
 - 2 NUMA domains (sockets) per node, 16 cores per NUMA domain. 2 hardware threads per physical core.
 - NUMA Domain 0: physical cores 0-15 (and logical cores 32-47)
NUMA Domain 1: physical cores 16-31 (and logical cores 48-63)
- Memory bandwidth is non-homogeneous among NUMA domains

Find Processor Info on a Mac Laptop

```
$ sysctl -n machdep.cpu.brand_string  
Intel(R) Core(TM) i7-8569U CPU @ 2.80GHz
```

```
$ system_profiler |grep Processor
```

...

Processor Name: Quad-Core Intel Core i7

Processor Speed: 2.8 GHz

Number of Processors: 1

...

Exercise: Node Information

- Characterize the processor/memory layout of your system
- Try on a Cori login node, a Cori Haswell and a Cori KNL node, and find out the differences

Process / Thread / Memory Affinity (1)

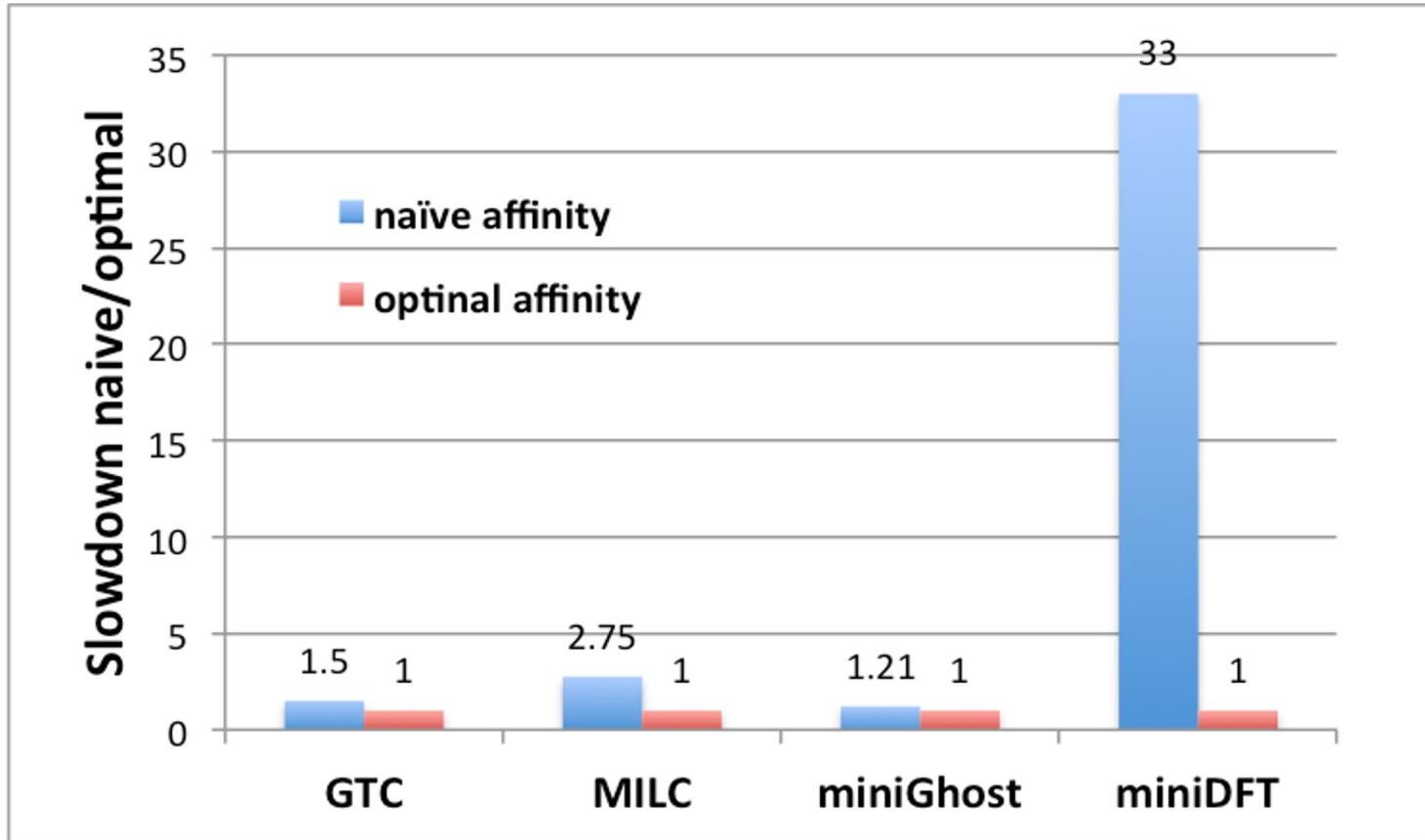
- **Process Affinity**: also called "CPU pinning", binds processes (MPI tasks, etc.) to a CPU or a range of CPUs on a node
 - It is important to spread MPI ranks evenly onto cores in different NUMA domains
- **Thread Affinity**: further binding threads to CPUs that are allocated to their parent process
 - **Thread affinity should be based on achieving process affinity first**
 - Threads forked by a certain MPI task have thread affinity binding close to the process affinity binding of their parent MPI task
 - **Do not over schedule CPUs for threads**

Process / Thread / Memory Affinity (2)

- **Memory Locality**: allocate memory as close as possible to the core on which the task that requested the memory is running
 - Applications should **use memory from local NUMA domain as much as possible**
- **Cache Locality**: reuse data in cache as much as possible
- Our goal is to promote **OpenMP standard settings for portability**
 - OMP_PLACES and OMP_PROC_BIND are preferred to vendor specific settings
- Correct process, thread and memory affinity is the basis for getting optimal performance. It is also essential for guiding further performance optimizations.

Naïve vs. Optimal Affinity

Application Benchmark Performance on Cori



OpenMP Thread Affinity

- Three main concepts:



OMP_PLACES
Environment Variable
(e.g. threads, cores,
sockets)

OMP_PROC_BIND
Environment Variable
or
proc_bind() clause
of parallel region

OMP_NUM_THREADS
Environment Variable
or
num_threads() clause
of parallel region

Courtesy of Oscar Hernandez, ORNL

Writing NUMA-aware OpenMP Code

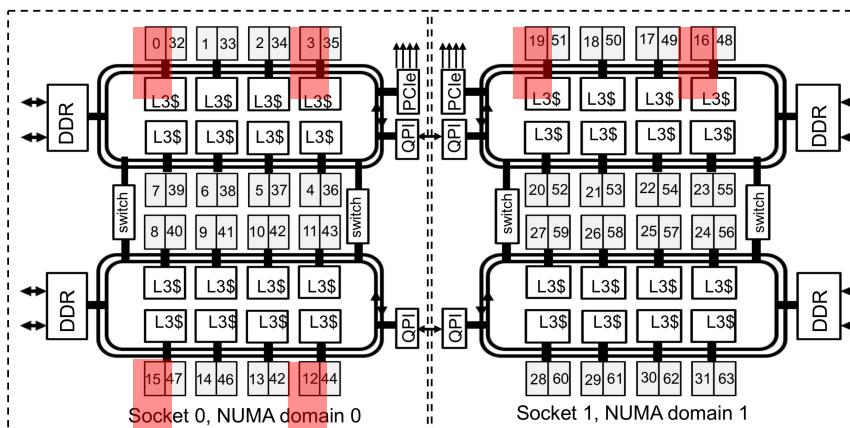
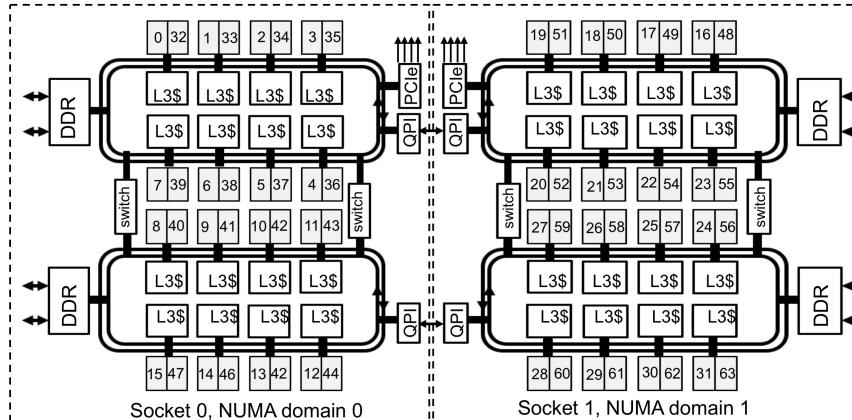
- ➡ • Control the places where threads are mapped
 - Place threads onto cores to optimize performance
 - Keep threads working on similar data close to each other
 - Maximize utilization of memory controllers by spreading threads out
- Processor binding ... Disable thread migration
 - By Default, an OS migrates threads to maximize utilization of resources on the chip.
 - To Optimize for NUMA, we need to turn off thread migration ... bind threads to a processor/core
- Memory Affinity
 - Maximize reuse of data in the cache hierarchy
 - Maximize reuse of data in memory pages

The Concept of Places

- The Operating System assigns logical CPU IDs to hardware threads.
- Recall ... the linux command `numactl -H` returns those numbers.
- A place: numbers between {}:
`export OMP_PLACES="{}0,1,2,3{}"`
- A place defines where threads can run

```
> export OMP_PLACES "{0, 3, 15, 12, 19, 16, 28, 31}"
> export NUM_THREADS= 6
```

```
#pragma omp parallel
{
    // do a bunch of cool stuff
}
```



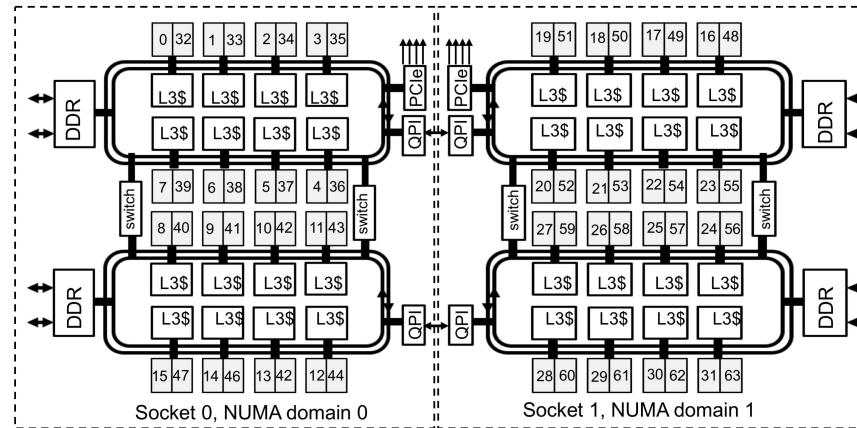
The Concept of Places

- The Operating System assigns logical CPU IDs to hardware threads.
- Recall ... the linux command `numactl -H` returns those numbers.
- Set with an environment variable:
`export OMP_PLACES="0,1,2,3"`
- Can also specify with `{lower-bound:length:stride}`

`OMP_PLACES="0,1,2,3" → OMP_PLACES="0:4:1" → OMP_PLACES="0:4"`
- Can define multiple places:

`OMP_PLACES="0,1,2,3},{4,6,8},{9,10,11,12}"`

`OMP_PLACES="0,4},{4,3:2},{9:4}"`



Default
Stride is 1

These are
equivalent

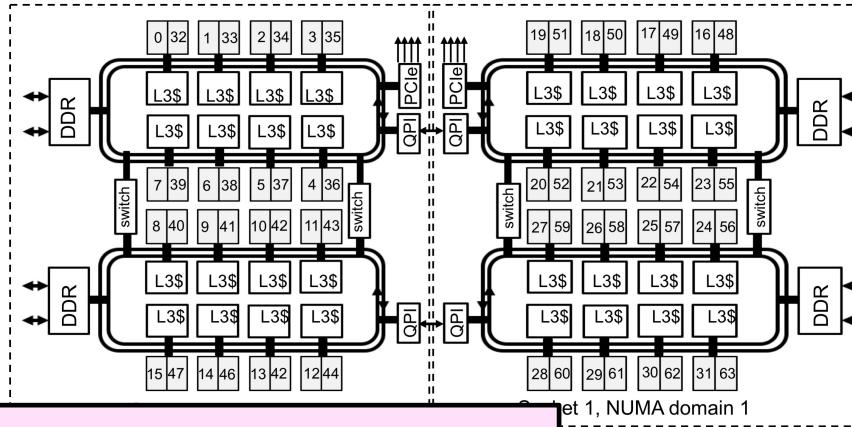
The Concept of Places

- The Operating System assigns logical CPU IDs to hardware threads.
- Recall ... the linux command `numactl -H` returns those numbers.

- Set with ~~an environment variable~~

Programmers can use OMP_PLACES for detailed control over the execution-units threads utilize. BUT ...

- Can a
OMP
 - The rules for mapping onto physical execution units are complicated.
 - PLACES expressed as numbers is non-portable
- There has to be an easier and more portable way to describe places
- Can



`OMP_PLACES="0,1,2,3},{4,6,8},{9,10,11,12}"`

These are equivalent

`OMP_PLACES="0,4},{4,3:2},{9:4}"`

Hardware Abstraction: OMP_PLACES

- OMP_PLACES environment variable
 - controls thread allocation
 - defines a series of places to which the threads are assigned
- It can be an abstract name or a specific list
 - **threads**: each place corresponds to a single hardware thread
 - **cores**: each place corresponds to a single core (having one or more hardware threads)
 - **sockets**: each place corresponds to a single socket (consisting of one or more cores)
 - a list with explicit place values of CPU ids, such as:
 - `export OMP_PLACES=" {0:4:2},{1:4:2}"` (equivalent to "`{0,2,4,6},{1,3,5,7}`")

- Examples:
 - `export OMP_PLACES=threads`
 - `export OMP_PLACES=cores`

Writing NUMA-aware OpenMP Code

- Control the places where threads are mapped
 - Place threads onto cores to optimize performance
 - Keep threads working on similar data close to each other
 - Maximize utilization of memory controllers by spreading threads out
- Processor binding ... Disable thread migration
 - By Default, an OS migrates threads to maximize utilization of resources on the chip.
 - To Optimize for NUMA, we need to turn off thread migration ... bind threads to a processor/core
- Memory Affinity
 - Maximize reuse of data in the cache hierarchy
 - Maximize reuse of data in memory pages

Mapping Strategy: OMP_PROC_BIND (1)

- Controls thread affinity within and between OpenMP places
- Allowed values:
 - **true**: the runtime will not move threads around between processors
 - **false**: the runtime may move threads around between processors
 - **close**: bind threads close to the master thread
 - **spread**: bind threads as evenly distributed (spreaded) as possible
 - **primary***: bind threads to the same place as the master thread
- The values **primary***, **close**, and **spread** imply the value **true**

Examples:

```
export OMP_PROC_BIND=spread  
export OMP_PROC_BIND=spread,close (for nested levels)
```

*the term “master” has been deprecated in OpenMP 5.1 and replaced with the term “primary”.

Mapping Strategy: OMP_PROC_BIND (2)

- Put threads far apart (spread) may improve aggregated memory bandwidth and available cache size for your application, but may also increase synchronization overhead
- Put threads “close” have the reverse impact as “spread”

Mapping Strategy: OMP_PROC_BIND (2)

Prototype example: 4 cores total, 2 hyperthreads per core, 4 OpenMP threads

- **none**: no affinity setting
- **close**: Bind threads as close to each other as possible

Node	Core 0		Core 1		Core 2		Core 3	
	HT1	HT2	HT1	HT2	HT1	HT2	HT1	HT2
Thread	0	1	2	3				

- **spread**: Bind threads as far apart as possible

Node	Core 0		Core 1		Core 2		Core 3	
	HT1	HT2	HT1	HT2	HT1	HT2	HT1	HT2
Thread	0		1		2		3	

- **master**: bind threads to the same place as the master thread

Various Methods to Set Number of Threads

1) Use num_threads clause

```
#pragma omp parallel num_threads(4)
{
    int ID = omp_get_thread_num();
    pooh(ID,A);
}
```

2) Call omp_set_num_threads API

```
omp_set_num_threads(4);
#pragma omp parallel
{
    int ID = omp_get_thread_num();
    pooh(ID,A);
}
```

3) Set runtime environment

```
export OMP_NUM_THREADS=4
#pragma omp parallel
{
    int ID = omp_get_thread_num();
    pooh(ID,A);
}
```

4) Do none of the three above.

Code will use an implementation dependent default number of threads defined by the compiler.

- Precedence: 1) > 2) > 3) > 4)
- You may get fewer threads than you requested, check with `omp_get_num_threads()`

Affinity Clauses for OpenMP Parallel Construct

- The `num_threads` and `proc_bind` clauses can be used
 - The values set with these clauses take precedence over values set by runtime environment variables
- Helps code portability

- Examples:

- C/C++:

```
#pragma omp parallel num_threads(2) proc_bind(spread)
```

- Fortran:

```
!$omp parallel num_threads (2) proc_bind (spread)
```

```
...
```

```
!$omp end parallel
```

Affinity Verification Methods

- NERSC provides pre-built binaries from a Cray code (`xthi.c`) to display process thread affinity

```
% srun -n 32 -c 8 --cpu-bind=cores check-mpi.intel.cori | sort -nk 4
```

```
Hello from rank 0, on nid02305. (core affinity = 0,1,68,69,136,137,204,205)
```

```
Hello from rank 1, on nid02305. (core affinity = 2,3,70,71,138,139,206,207)
```

- Use portable OpenMP environment variables `OMP_DISPLAY_AFFINITY` and `OMP_AFFINITY_FORMAT` (in OpenMP 5.0)

- Automatically displays affinity info when `OMP_DISPLAY_AFFINITY=true`
- Can set custom `OMP_DISPLAY_AFFINITY_FORMAT`
- Also has runtime APIs such as `omp_display_affinity` and `omp_capture_affinity`

OMP_AFFINITY_FORMAT Fields

Short Name	Long name	Meaning
L	thread_level	from omp_get_level()
n	thread_num	from omp_get_thread_num()
a	thread_affinity	the numerical identifiers of the processors the current thread is binding to, in the format of a comma separated list of OpenMP thread places
h	host	host or node name
p	process_id	process id used by the implementation (such as the process id for the MPI process)
N	num_threads	from omp_get_num_threads()
A	ancestor_tnum	from omp_get_ancestor_thread_num(). One level up only.

```
% export OMP_DISPLAY_AFFINITY=true
% export OMP_AFFINITY_FORMAT="host=%h, pid=%p, thread_num=%n, thread affinity=%a"
host=nid02496, pid=150147, thread_num=0, thread affinity=0
host=nid02496, pid=150147, thread_num=1, thread affinity=4
% export OMP_AFFINITY_FORMAT="Thread Affinity: %0.3L %.10n %.20{thread_affinity} %.15h"
Thread Affinity: 001      0      0-1,16-17      nid003
Thread Affinity: 001      1      2-3,18-19      nid003
```

Sample Nested OpenMP Program

```
#include <omp.h>
#include <stdio.h>
void report_num_threads(int level)
{
    #pragma omp single {
        printf("Level %d: number of threads in the
team: %d\n", level, omp_get_num_threads());
    }
}
int main()
{
    omp_set_dynamic(0);
    #pragma omp parallel num_threads(2) {
        report_num_threads(1);
        #pragma omp parallel num_threads(2) {
            report_num_threads(2);
            #pragma omp parallel num_threads(2) {
                report_num_threads(3);
            }
        }
    }
    return(0);
}
```

% ./a.out

Level 1: number of threads in the team: 2

Level 2: number of threads in the team: 1

Level 3: number of threads in the team: 1

Level 2: number of threads in the team: 1

Level 3: number of threads in the team: 1

% export OMP_NESTED=true

% export OMP_MAX_ACTIVE_LEVELS=3

% ./a.out

Level 1: number of threads in the team: 2

Level 2: number of threads in the team: 2

Level 2: number of threads in the team: 2

Level 3: number of threads in the team: 2

Level 3: number of threads in the team: 2

Level 3: number of threads in the team: 2

Level 3: number of threads in the team: 2

Level 0: P0

Level 1: P0 P1

Level 2: P0 P2; P1 P3

Level 3: P0 P4; P2 P5; P1 P6; P3 P7

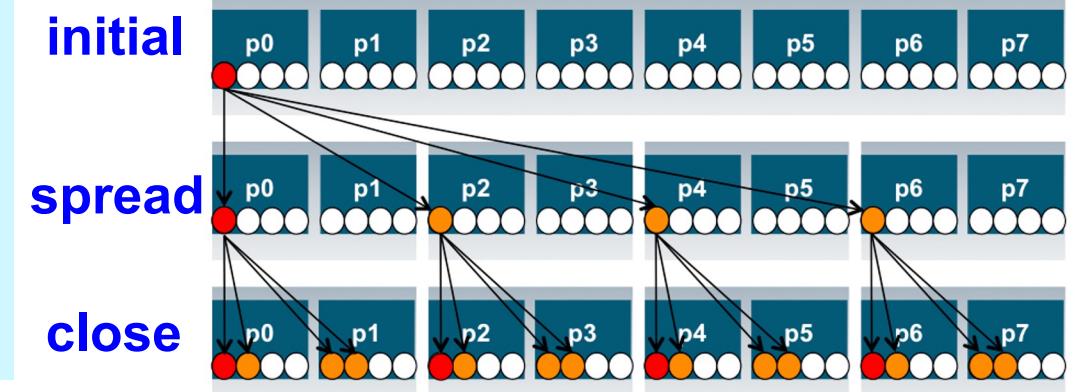
Process and Thread Affinity in Nested OpenMP

- A combination of OpenMP environment variables and runtime flags are needed for different compilers and different batch schedulers on different systems

```
#pragma omp parallel proc_bind(spread)  
#pragma omp parallel proc_bind(close)
```

Example: Use Intel compiler with SLURM on Cori Haswell:
export OMP_NESTED=true
export OMP_MAX_ACTIVE_LEVELS=2
export OMP_NUM_THREADS=4,4
export OMP_PROC_BIND=spread,close
export OMP_PLACES=threads
srun -n 4 -c 16 --cpu_bind=cores ./code.exe

Illustration of a system with:
2 sockets, 4 cores per socket,
4 hyper-threads per core



- Use num_threads clause in source codes to set threads for nested regions
- For most other non-nested regions, use OMP_NUM_THREADS environment variable for simplicity and flexibility

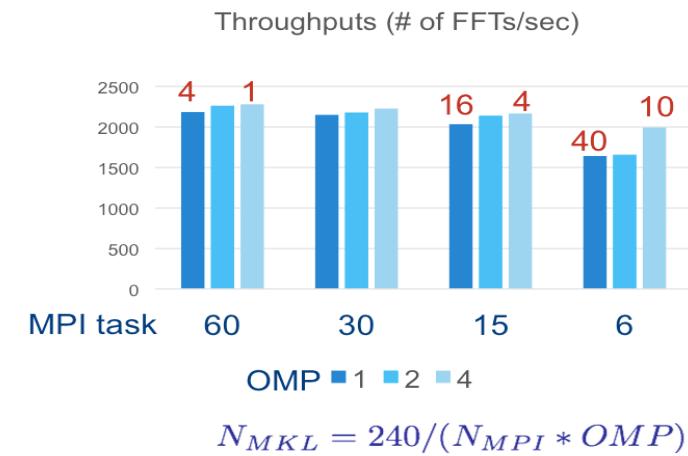
When to Use Nested OpenMP

- Beneficial to use nested OpenMP to allow more fine-grained thread parallelism
- Some application teams are exploring with nested OpenMP to allow more fine-grained thread parallelism
 - Hybrid MPI/OpenMP not using node fully packed
 - Top level OpenMP loop does not use all available threads
 - Multiple levels of OpenMP loops are not easily collapsed
 - Certain computational intensive kernels could use more threads
 - MKL can use extra cores with nested OpenMP
- Nested level can be arbitrarily deep

Use Multiple Threads in MKL

- By Default, in OpenMP parallel regions, only 1 thread will be used for MKL calls.
 - MKL_DYNAMICS is true by default
- Nested OpenMP can be used to enable multiple threads for MKL calls. **Treat MKL as a nested inner OpenMP region.**
- Sample settings

```
export OMP_NESTED=true
export OMP_PLACES=cores
export OMP_PROC_BIND=sprad,close
export OMP_NUM_THREADS=6,4
export MKL_DYNAMICS=false
export OMP_MAX_ACTIVE_LEVELS=2
```



FFT3D on KNC, Ng=64³ example
Courtesy of Jeongnim Kim, Intel

*KNC: Intel® Xeon Phi™ processor (Knights Corner) ... the first generation co-processor version of the chip.

Exercise: Affinity Verification

- Run the “Hello World” code, use OMP_DISPLAY_AFFINITY to observe affinity status
- Change thread binding and number of threads and see how affinity status changes

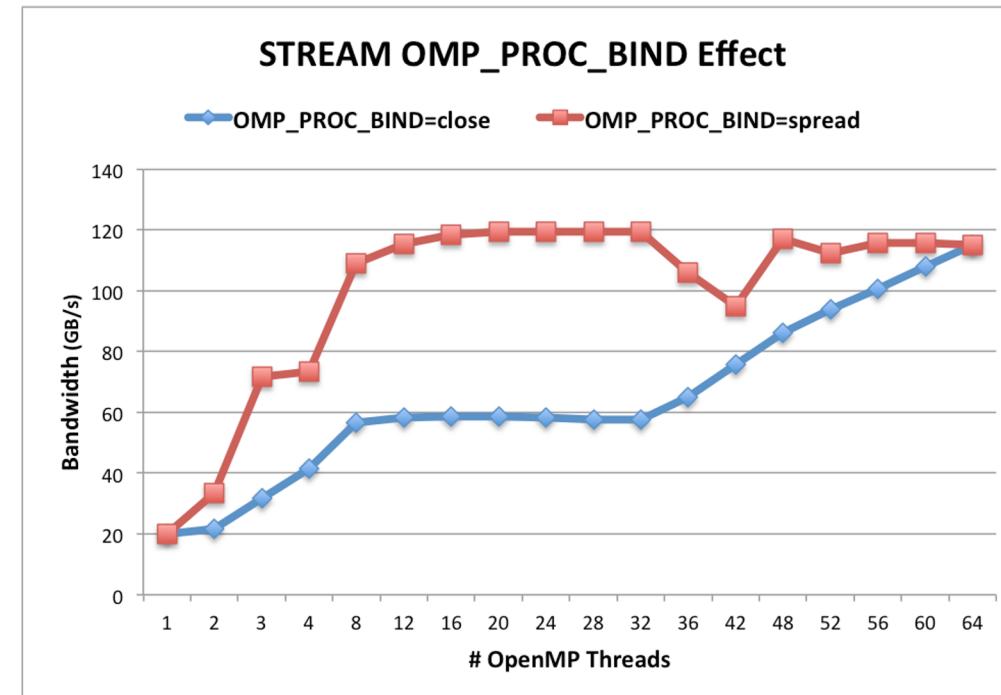
OMP_PROC_BIND Choices for STREAM Benchmark

OMP_NUM_THREADS=32
OMP_PLACES=threads

OMP_PROC_BIND=close
Threads 0 to 31 bind to CPUs 0,32,1,33,2,34,...15,47. All threads are in the first socket. The second socket is idle. Not optimal.

OMP_PROC_BIND=spread
Threads 0 to 31 bind to CPUs 0,1,2,... to 31. Both sockets and memory are used to maximize memory bandwidth.

Blue: OMP_PROC_BIND=close
Red: OMP_PROC_BIND=spread
Both with First Touch



Exercise: STREAM Benchmark

- Use the STREAM benchmark code: C/affinity/stream.c
 - Sample batch script: “run_stream_sample.sh”

```
% sbatch <job_script>
```
 - STREAM memory bandwidth results: check “Best Rate” for “Triad” in the output
 - Experiment with different OMP_NUM_THREADS, OMP_PROC_BIND, and OMP_PLACES, and OMP_DISPLAY_AFFINITY settings to check thread affinity output and performance result
 - Run with 8, 16, 32, 48, 64 threads, and OMP_PROC_BIND=spread or close
- Compare your results with the previous STREAM plot

Writing NUMA-aware OpenMP Code

- Control the places where threads are mapped
 - Place threads onto cores to optimize performance
 - Keep threads working on similar data close to each other
 - Maximize utilization of memory controllers by spreading threads out
- Processor binding ... Disable thread migration
 - By Default, an OS migrates threads to maximize utilization of resources on the chip.
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- Memory Affinity
 - Maximize reuse of data in the cache hierarchy
 - Maximize reuse of data in memory pages



Memory Affinity: “First Touch” memory

Step 1.1 Initialization by master thread only

```
for (j=0; j<VectorSize; j++) {  
    a[j] = 1.0; b[j] = 2.0; c[j] = 0.0;}
```

Step 1.2 Initialization by all threads

```
#pragma omp parallel for  
for (j=0; j<VectorSize; j++) {  
    a[j] = 1.0; b[j] = 2.0; c[j] = 0.0;}
```

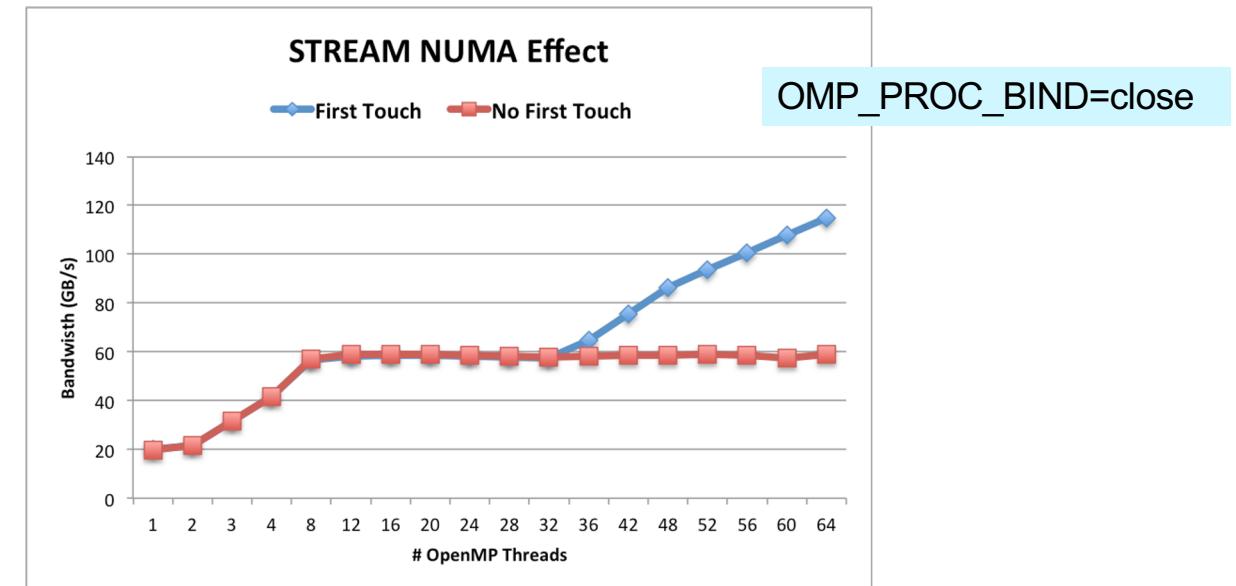
Step 2 Compute

```
#pragma omp parallel for  
for (j=0; j<VectorSize; j++) {  
    a[j]=b[j]+d*c[j];}
```

- Memory affinity is not defined when memory was allocated, instead it will be defined at initialization.
- Memory will be local to the thread which initializes it. This is called **first touch** policy.
- Hard to do “perfect touch” for real applications. General recommendation is to [use number of threads fewer than number of CPUs \(one or more MPI tasks\) per NUMA domain](#).

Red: step 1.1 + step 2. No First Touch

Blue: step 1.2 + step 2. First Touch

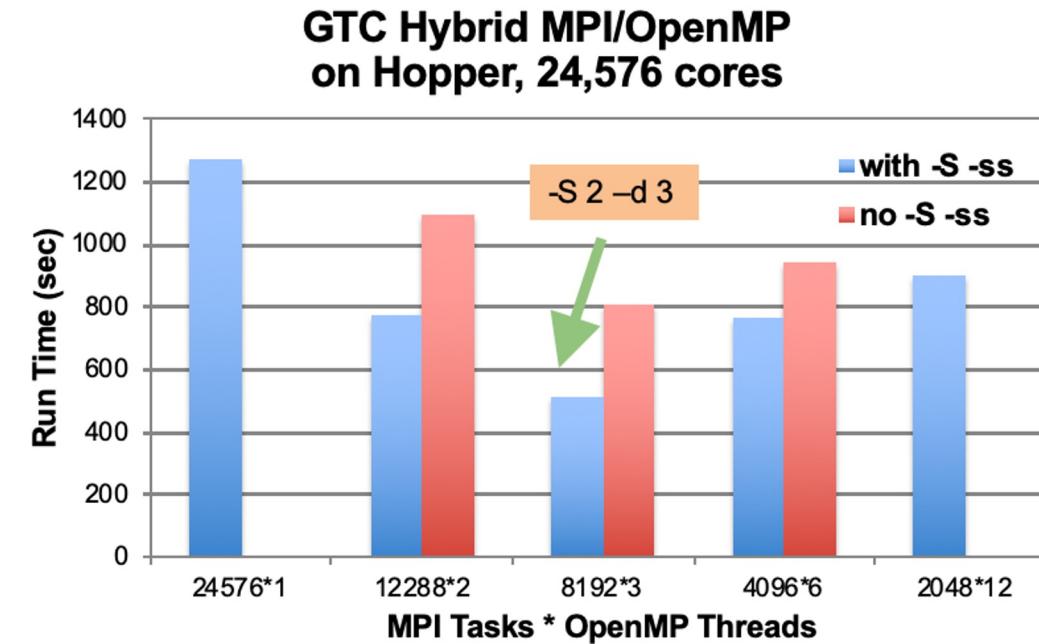
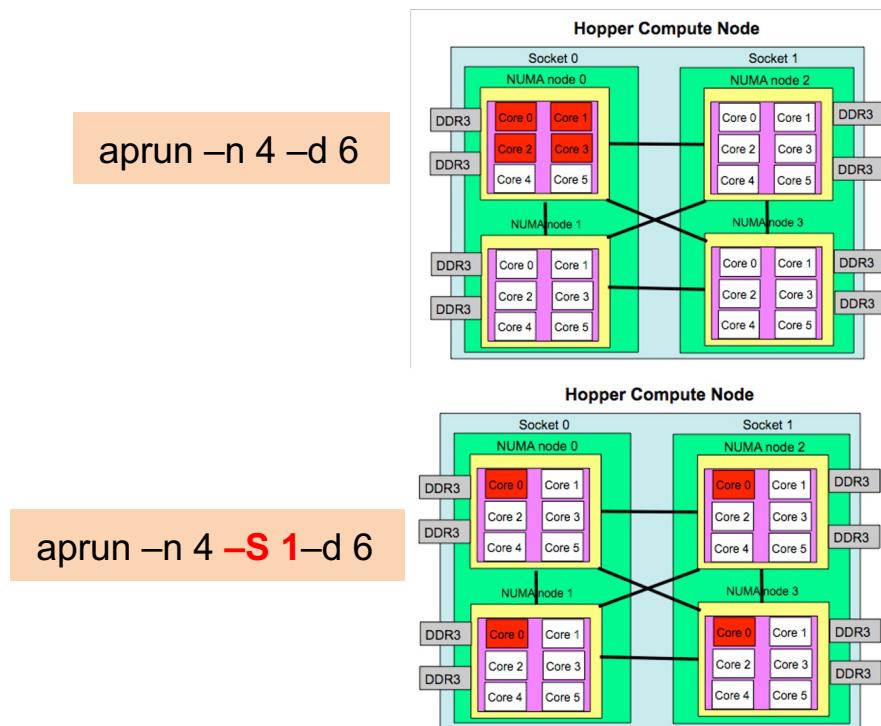


“Perfect Touch” is Hard

- Hard to do “perfect touch” for real applications
- General recommendation: use number of threads fewer than number of CPUs per NUMA domain
- In the previous example, there are 16 cores (32 CPUs) per NUMA domain. Sample run options:
 - 2 MPI tasks, 1 MPI task per NUMA domain, with 32 OpenMP threads (if using hyperthreads) or 16 OpenMP threads (if not using hyperthreads) per MPI task
 - 4 MPI tasks, 2 MPI tasks per NUMA domain, with 16 OpenMP threads (if using hyperthreads) or 8 OpenMP threads (if not using hyperthreads) per MPI task
 - ...

MPI Process Affinity Example: aprun “-S” Option

- Important to spread MPI ranks evenly onto different NUMA nodes
- Use the “-S” option: [specify #MPI_tasks per NUMA domain](#)
- The example below was from an XE6 system (NERSC Hopper)



Exercise: Importance of First Touch

- Do the same STREAM experiments with the no first touch code: “stream_nft.c” to understand the impact of first touch
 - Experiment with different OMP_NUM_THREADS, OMP_PROC_BIND, and OMP_PLACES, and OMP_DISPLAY_AFFINITY settings to check thread affinity output and performance result
 - Run with 8, 16, 32, 48, 64 threads, and OMP_PROC_BIND=spread or close
- Compare your results with the previous STREAM plot

OpenMP task-to-data Affinity (in OpenMP 5.0)

- Affinity hints can be provided for OpenMP tasks, resulting data to be closer to tasks
- Useful for multi-socket systems

```
void task_affinity() {  
    double* B;  
#pragma omp task shared(B) affinity(A[0:N])  
    B = init_B_and_important_computation(A);  
  
#pragma omp task firstprivate(B) affinity(B[0:N])  
    important_computation_too(B);  
  
#pragma omp taskwait  
}
```

Memory Allocators (in OpenMP 5.0)

Allocator name	Storage selection intent
omp_default_mem_alloc	use default storage
omp_large_cap_mem_alloc	use storage with large capacity
omp_const_mem_alloc	use storage optimized for read-only variables
omp_high_bw_mem_alloc	use storage with high bandwidth
omp_low_lat_mem_alloc	use storage with low latency
omp_cgroup_mem_alloc	use storage close to all threads in the contention group of the thread requesting the allocation
omp_pteam_mem_alloc	use storage that is close to all threads in the same parallel region of the thread requesting the allocation
omp_thread_local_mem_alloc	use storage that is close to the thread requesting the allocation

- Support versatile types of memory available on current and future systems: DDR, High-Bandwidth Memory (HBM), non-volatile memory, constant memory
- Memory allocators define types of memory that variables can be allocated to, such as large capacity, low latency, cgroup, thread local, etc.

Using Memory Allocators

```
void allocator_example(omp_allocator_t *my_allocator) {  
    int a[M], b[N];  
    #pragma omp allocate(a) allocator(omp_high_bw_mem_alloc)  
    #pragma omp allocate(b) // use default OMP_ALLOCATOR  
  
    double *p = (double *) omp_alloc(N*M*sizeof(*p), my_allocator);  
  
    #pragma omp parallel private(a) allocate(omp_low_lat_mem_alloc:a)  
    {  
        some_parallel_code();  
    }  
    omp_free(p);  
}
```

A NUMA Case study

Benchmarking ... I Must Control Everything!

- Goal: To compare different programming systems applied to the same problem:
 - We must control everything we can to make sure any observed differences are due to the different programming systems.
- We need to know exactly which cores we are using and how thread IDs map onto cores ... so we can understand data detailed memory movement and make sure it's the same between the different test cases.

Step 1: Know Your System

- My system did not have numactl or Hwloc. So I went with my third option lscpu (note: I'm only showing a subset of the actual output):

```
$ lscpu
Architecture:          x86_64
CPU op-mode(s):        32-bit, 64-bit
Byte Order:            Little Endian
Address sizes:         46 bits physical, 48 bits virtual
CPU(s):                72
On-line CPU(s) list:   0-71
Thread(s) per core:    2
Core(s) per socket:    18
Socket(s):             2
NUMA node(s):          2
Vendor ID:             GenuineIntel
CPU family:            6
Model:                 63
Model name:            Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30GHz
Stepping:               2
CPU MHz:               1197.539
CPU max MHz:           3600.0000
CPU min MHz:           1200.0000
L1d cache:              1.1 MiB
L1i cache:              1.1 MiB
L2 cache:               9 MiB
L3 cache:               90 MiB
NUMA node0 CPU(s):      0-17,36-53
NUMA node1 CPU(s):      18-35,54-71
```

SMT enabled ... two HW threads per core

2 CPUs (sockets) with 18 physical cores per CPU

Note: a HW thread is a CPU (or core) as far as the OS is concerned. These two lines show you the numbering of these “cores”.

Step 1: Know Your System

- My system did not have numactl or Hwloc. So I went with my third option lscpu (note: I'm only showing a subset of the actual output):

```
$ lscpu
Architecture:          x86_64
CPU op-mode(s):        32-bit, 64-bit
Byte Order:            Little Endian
Address sizes:         46 bits physical, 48 bits virtual
CPU(s):                72
On-line CPU(s) list:   0-71
Thread(s) per core:    2
Core(s) per socket:    18
Socket(s):             2
NUMA node(s):          2
Vendor ID:             GenuineIntel
CPU family:            6
Model:                 63
Model name:            Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30GHz
Stepping:               2
CPU MHz:               1197.539
CPU max MHz:           3600.0000
CPU min MHz:           1200.0000
L1d cache:              1.1 MiB
L1i cache:              1.1 MiB
L2 cache:               9 MiB
L3 cache:               90 MiB
NUMA node0 CPU(s):      0-17,36-53
NUMA node1 CPU(s):      18-35,54-71
```

SMT enabled ... two HW threads per core

2 CPUs (sockets) with 18 physical cores per CPU

The numbering of these “cores” (in 2 sockets).

0/36	1/37	2/38	3/39	4/40	5/41	6/42	7/43	8/44
9/45	10/46	11/47	12/48	13/49	14/50	15/51	16/52	17/53
18/54	19/55	20/56	21/57	22/58	23/59	24/60	25/61	26/62
27/63	28/64	29/65	30/66	31/67	32/68	33/69	34/70	35/71

Setup a Runscript (so you can reproduce the computations later)

```
#!/usr/bin/env bash
# Run script for DGEMM with C and OpenMP

# Define shared parameters for the calculations we will run
BLOCK=0
ORDER=1000
ITERS=5

# setup environment for the intel compilers
source /opt/intel/compilers_and_libraries_2020.4.304/linux/bin/compilervars.sh -arch intel64

# Setup display of mapping from OpenMP threads to "hardware" threads.
export OMP_DISPLAY_AFFINITY=true
export OMP_AFFINITY_FORMAT="Thrd Lev=%3L, thrd_num=%5n, thrd_aff=%15A"

# Enable explicit affinity control.
export OMP_PLACES="{0},{1},{2},{3},{4},{5},{6},{7},{8},{9},{10},{11},{12},{13},{14},{15},{16}"
export OMP_PROC_BIND=close

./dgemm 8 $ITERS $ORDER $BLOCK
./dgemm 16 $ITERS $ORDER $BLOCK
```

A NUMA Case Study: Results

Parallel Research Kernels version 2.17

OpenMP Dense matrix-matrix multiplication

Thrd Lev=1 , thrd_num=0 , thrd_aff=0

Thrd Lev=1 , thrd_num=4 , thrd_aff=4

Thrd Lev=1 , thrd_num=3 , thrd_aff=3

Thrd Lev=1 , thrd_num=5 , thrd_aff=5

Thrd Lev=1 , thrd_num=1 , thrd_aff=1

Thrd Lev=1 , thrd_num=2 , thrd_aff=2

Thrd Lev=1 , thrd_num=6 , thrd_aff=6

Thrd Lev=1 , thrd_num=7 , thrd_aff=7

Matrix order = 1000

Number of threads = 8

Rate : 21650.601956 +/- 1589.413250 MFlops/s

Notice the one-to-one mapping of thread ID onto hardware thread.

Normally, this is going too far, but for benchmarking, this is a handy trick.

Parallel Research Kernels version 2.17

OpenMP Dense matrix-matrix multiplication

Thrd Lev=1 , thrd_num=0 , thrd_aff=0

Thrd Lev=1 , thrd_num=13 , thrd_aff=13

Thrd Lev=1 , thrd_num=4 , thrd_aff=4

Thrd Lev=1 , thrd_num=11 , thrd_aff=11

Thrd Lev=1 , thrd_num=10 , thrd_aff=10

Thrd Lev=1 , thrd_num=8 , thrd_aff=8

Thrd Lev=1 , thrd_num=9 , thrd_aff=9

Thrd Lev=1 , thrd_num=1 , thrd_aff=1

Thrd Lev=1 , thrd_num=3 , thrd_aff=3

Thrd Lev=1 , thrd_num=2 , thrd_aff=2

Thrd Lev=1 , thrd_num=12 , thrd_aff=12

Thrd Lev=1 , thrd_num=7 , thrd_aff=7

Thrd Lev=1 , thrd_num=6 , thrd_aff=6

Thrd Lev=1 , thrd_num=5 , thrd_aff=5

Thrd Lev=1 , thrd_num=14 , thrd_aff=14

Thrd Lev=1 , thrd_num=15 , thrd_aff=15

Matrix order = 1000

Number of threads = 16

Rate : 38765.867067 +/- 3303.460980 MFlops/s

Obtain Optimal Affinity on Cori KNL Example

KNL Compute Nodes

A Cori KNL node has 68 cores/272 CPUs, 96 GB DDR memory, 16 GB high bandwidth on package memory (MCDRAM)

Arrangement of Hardware Threads for 68 Core KNL																				
Core # →	0	1	2	3	...	16	17	18	...	33	34	35	...	50	51	52	...	65	66	67
HW Thread #	0	1	2	3	...	16	17	18	...	33	34	35	...	50	51	52	...	65	66	67
	68	69	70	71	...	84	85	86	...	101	102	103	...	118	119	120	...	133	134	135
	136	137	138	139	...	152	153	154	...	169	170	171	...	186	187	188	...	201	202	203
	204	205	206	207	...	220	221	222	...	237	238	239	...	254	255	256	...	269	270	271

A [quad,cache](#) node (default setting) has only [1 NUMA node](#) with all CPUs on the NUMA node 0 (DDR memory). MCDRAM is hidden from the “numactl -H” result since it is a cache.

Can We Just Do a Naive `srun`?

Example: 16 MPI tasks x 8 OpenMP threads per task on a single 68-core KNL quad,cache node:

```
% export OMP_NUM_THREADS=8  
% export OMP_PROC_BIND=spread      (other choice are "close","master","true","false")  
% export OMP_PLACES=threads       (other choices are: cores, sockets, and various ways to specify explicit lists, etc.)
```

```
% srun -n 16 ./xthi |sort -k4n,6n      or % mpirun -n 16 ./xthi  
Hello from rank 0, thread 0, on nid02304. (core affinity = 0)  
Hello from rank 0, thread 1, on nid02304. (core affinity = 144)      (on physical core 8)  
Hello from rank 0, thread 2, on nid02304. (core affinity = 17)  
Hello from rank 0, thread 3, on nid02304. (core affinity = 161)      (on physical core 25)  
...  
Hello from rank 1, thread 0, on nid02304. (core affinity = 0)  
Hello from rank 1, thread 1, on nid02304. (core affinity = 144)
```

It is a mess! e.g., thread 0 for rank 0, and thread 1 for rank 1 are on same physical core 0

MPI Process Affinity: Selected Slurm `srun` Options

- `--cpu-bind=threads`
Automatically generate masks binding tasks to threads
- `--cpu-bind=cores`
Automatically generate masks binding tasks to cores
- `--cpu-bind=sockets`
Automatically generate masks binding tasks to sockets
- `--cpu-bind=map_cpu:<cpulist>`
Bind by setting CPU masks on tasks (or ranks)
- `--cpu-bind=map_ldom:<NUMA_domain_list>`
Bind by mapping NUMA locality domain IDs to tasks
(ldom means logical domain)

Example mpirun or srun Commands: Fix the Problem

- The reason is #MPI tasks is not divisible by 68!
 - Each MPI task is getting $68 \times 4 / \# \text{MPI tasks}$ of logical cores as the domain size
 - MPI tasks are crossing tile boundaries
 - Let's set number of logical cores per MPI task manually by wasting extra 4 cores on purpose, which is $256 / \# \text{MPI tasks}$
- Cray MPICH with Aries network using native SLURM
 - `% srun -n 16 -c 16 --cpu_bind=cores ./code.exe`
Notes: Here the value for `-c` is also set to number of logical cores per MPI task, i.e., $256 / \# \text{MPI tasks}$.
 - Intel MPI with Omni Path using mpirun:
 - `% export I_MPI_PIN_DOMAIN=16`
 - `% mpirun -n 16 ./code.exe`

Now It Looks Good!

Process/thread affinity are good! (Marked first 6 and last MPI tasks only)

Intel KNL Quad,Flat Node Example

Cori KNL quad,flat node example
68 cores (272 CPUs)

% numactl –H

```
available: 2 nodes (0-1)
node 0 cpus: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82
83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117
118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147
148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177
178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207
208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237
238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267
268 269 270 271
node 0 size: 96723 MB
node 0 free: 93924 MB
node 1 cpus:
node 1 size: 16157 MB
node 1 free: 16088 MB
node distances:
node 0 1
0: 10 31
1: 31 10
```

- The quad,flat mode has only 2 NUMA nodes with all CPUs on the NUMA node 0 (DDR memory).
- And NUMA node 1 has MCDRAM (high bandwidth memory).

Essential Runtime Settings for KNL MCDRAM Memory Affinity

- In quad, cache mode, no special setting is needed to use MCDRAM
- In quad,flat mode, using quad,flat as an example
 - NUMA node 1 is MCDRAM
- Enforced memory mapping to MCDRAM
 - If using >16 GB, malloc will fail
 - Use “**numactl -m 1 ./myapp**” as the executable
(instead of “./myapp”)
- Preferred memory mapping to MCDRAM
 - If using >16 GB, malloc will spill to DDR
 - Use “**numactl -p 1 ./myapp**” as the executable
(instead of “./myapp”)

Process and Thread Affinity Best Practices

- Achieving best data locality, and optimal process and thread affinity is crucial in getting good performance with MPI/OpenMP, yet **not straightforward**
 - Understand the [node architecture](#) with tools such as “numactl -H” first
 - Set [correct cpu-bind](#) and [OMP_PLACES](#) options
 - Always use simple examples with the same settings for your real application to [verify affinity](#) first or check with [OMP_DISPLAY_AFFINITY](#)
 - For nested OpenMP, set [OMP_PROC_BIND=spread,close](#) is recommended
- Optimize code for memory affinity
 - Pay special attention to [avoid false sharing](#)
 - Exploit first touch data policy, or use [at least 1 MPI task per NUMA domain](#)
 - [Optimize code for cache locality](#)
 - Compare performance with [put threads close or far apart \(spread\)](#)
 - Use [omp_allocator](#)
 - Use [numactl -m](#) option to explicitly request memory allocation in specific NUMA domain (such as high bandwidth memory in KNL)

Extras: Two short extra sections

- • Fortran and OpenMP
- OpenMP compilers on Apple laptops

Fortran and OpenMP

- We were careful to design the OpenMP constructs so they cleanly map onto C, C++ and Fortran.
- There are a few syntactic differences that once understood, will allow you to move back and forth between languages.
- In the specification, language specific notes are included when each construct is defined.

OpenMP:

Some syntax details for Fortran programmers

- Most of the constructs in OpenMP are compiler directives.

- For Fortran, the directives take one of the forms:

`C$OMP construct [clause [clause]...]`

`!$OMP construct [clause [clause]...]`

`*$OMP construct [clause [clause]...]`

- The OpenMP include file and lib module

`use omp_lib`

`include "omp_lib.h"`

OpenMP: Structured Blocks (Fortran)

- Most OpenMP constructs apply to structured blocks.
- Structured block: a block of code with one point of entry at the top and one point of exit at the bottom.
- The only “branches” allowed are STOP statements in Fortran and exit() in C/C++.

```
C$OMP PARALLEL  
10 wrk(id) = garbage(id)  
     res(id) = wrk(id)**2  
     if(conv(res(id)) goto 10  
C$OMP END PARALLEL  
     print *,id
```

A structured block

```
C$OMP PARALLEL  
10 wrk(id) = garbage(id)  
30 res(id)=wrk(id)**2  
     if(conv(res(id))goto 20  
     go to 10  
C$OMP END PARALLEL  
     if(not_DONE) goto 30  
20 print *, id
```

Not A structured block

OpenMP:

Structured Block Boundaries

- In Fortran: a block is a single statement or a group of statements between directive/end-directive pairs.

```
C$OMP PARALLEL  
10  wrk(id) = garbage(id)  
     res(id) = wrk(id)**2  
     if(conv(res(id))) goto 10  
C$OMP END PARALLEL
```

```
C$OMP PARALLEL DO  
do I=1,N  
    res(I)=bigComp(I)  
end do  
C$OMP END PARALLEL DO
```

- The “construct/end construct” pairs is done anywhere a structured block appears in Fortran. Some examples:
 - DO ... END DO
 - PARALLEL ... END PARREL
 - CRITICAL ... END CRITICAL
 - SECTION ... END SECTION
 - SECTIONS ... END SECTIONS
 - SINGLE ... END SINGLE
 - MASTER ... END MASTER

Runtime Library Routines

- The include file or module defines parameters
 - Integer parameter `omp_lock_kind`
 - Integer parameter `omp_nest_lock_kind`
 - Integer parameter `omp_sched_kind`
 - Integer parameter `openmp_version`
 - With value that matches C's `_OPENMP` macro
- Fortran interfaces are similar to those used with C
 - Subroutine `omp_set_num_threads(num_threads)`
 - Integer function `omp_get_num_threads()`
 - Integer function `omp_get_thread_num()\`
 - Subroutine `omp_init_lock(svar)`
 - Integer(kind=omp_lock_kind) svar
 - Subroutine `omp_destroy_lock(svar)`
 - Subroutine `omp_set_lock(svar)`
 - Subroutine `omp_unset_lock(svar)`

Extras: Two short extra sections

- Fortran and OpenMP
- ➡ • OpenMP compilers on Apple laptops

OpenMP Compilers on Apple Laptops: MacPorts

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

```
sudo port selfupdate
```

Update to latest version of
MacPorts

```
sudo port install gcc-10
```

Grab version 9 gnu
compilers (5-10 mins)

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

List versions of gcc on your
system

```
sudo port select --set gcc mp-gcc-10
```

Select the mp enabled version of
the most recent gcc release

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

Test the installation with a simple
program

Download tutorial materials onto your laptop:

git clone <https://github.com/tgmattso/OmpCommonCore.git>

OpenMP Compilers on Apple Laptops: Homebrew

- An alternate way to use OpenMP on your Apple laptop:
- Install Homebrew. If Homebrew is already installed, skip to the install gcc section.

```
echo $SHELL
```

Check that you are running bash shell for ruby. Use the ruby to install homebrew.

```
/usr/bin/ruby -e "$(curl -fsSL  
https://raw.githubusercontent.com/Homebrew/install/master/install)"
```

```
brew install gcc
```

```
which gcc-10
```

In my case, homebrew installed a new version of gcc called it gcc-9

```
gcc-10 -fopenmp hello_par.c  
./a.out
```

Test the installation with a simple program

```
export OMP_NUM_THREADS=8  
./a.out
```

Download tutorial materials onto your laptop:
git clone <https://github.com/tgmattso/OmpCommonCore.git>