An Introduction to Parallel Programming: (using OpenMP)

merly.ai

AI supporting software engineering

Tim Mattson (retired from Intel Aug'2023, University of Bristol and Merly.ai)

Download tutorial materials onto your laptop: git clone https://github.com/tgmattso/ATPESC.git

An brief aside about the origins of parallel programming models

The Bad Old days …

Parallel programming environments in the 90's

ABCPL
ACE
ACT++
Active messages
Adl
Adsmith
ADDAP
AFAPI
ALWAN
AM
AMDC
AppLeS
Amoeba
ARTS
Athapascan-0b
Aurora
Automap
bb_threads
Blaze
BSP
BlockComm
C*.
"C* in C
C**
CarlOS
Cashmere
C4
CC++
Chu
Charlotte
Charm
Charm++
Cid
Cilk
CM-Fortran
Converse
Code
COOL

CORRELATE
CPS
CRL
CSP
Cthreads
CUMULVS
DAGGER
DAPPLE
Data Parallel C
DC++
DCE++
DDD
DICE.
DIPC
DOLIB
DOME
DOSMOS.
DRL
DSM-Threads
Ease .
ECO
Eiffel
Eilean
Emerald
EPL
Excalibur
Express
Falcon
Filaments
FM
FLASH
The FORCE
Fork
Fortran-M
FX
GA
GAMMA
Glenda

GLU
GUARD
HAsL.
Haskell
HPC++
JAVAR.
HORUS
HPC
HPF
IMPACT
ISIS.
JAVAR
JADE
Java RMI
javaPG
JavaSpace
JIDL
Joyce
Khoros
Karma
KOAN/Fortran-S
LAM
Lilac
Linda
JADA
WWWinda
ISETL-Linda
ParLin
Eilean
P4-Linda
Glenda
POSYBL
Objective-Linda
LiPS
Locust
Lparx
Lucid
Maisie
Manifold

Mentat
Legion
Meta Chaos
Midway
Millipede
CparPar
Mirage
MpC
MOSIX
Modula-P
Modula-2*
Multipol
MPI
MPC++
Munin
Nano-Threads
NESL
NetClasses++
Nexus
Nimrod
NOW
Objective Linda
Occam
Omega
OpenMP
Orca
OOF90
P++
P3L
p4-Linda
Pablo
PADE
PADRE
Panda
Papers
AFAPI.
Para++
Paradigm

Parafrase2
Paralation
Parallel-C++
Parallaxis
ParC
ParLib++
ParLin
Parmacs
Parti
pC
pC++
PCN
PCP:
PH
PEACE
PCU
PET
PETSc
PENNY
Phosphorus
POET.
Polaris
POOMA
POOL-T
PRESTO
P-RIO
Prospero
Proteus
QPC++
PVM
PSI
PSDM
Quake
Quark
Quick Threads
Sage++
SCANDAL
SAM

pC++
SCHEDULE
SciTL
POET
SDDA.
SHMEM
SIMPLE
Sina
SISAL.
distributed smalltalk
SMI.
SONiC
Split-C.
SR
Sthreads
Strand.
SUIF.
Synergy
Telegrphos
SuperPascal
TCGMSG.
Threads.h++.
TreadMarks
TRAPPER
uC++
UNITY
UC
V
ViC*
Visifold V-NUS
VPE
Win32 threads
WinPar
WWWinda
XENOOPS
XPC
Zounds
ZPL

A combination of vendors wanting to lock-down applications and the fact that its "fun" to create new programming environments created chaos for application developers

History of MPI

Workstation vendors wanted into the HPC market

PVM was great but didn't support quality SW engineering

Hardware:
By the early 90's, massively parallel processors (MPPs) and the new trend with clusters convinced even the skeptics that the "killer micros" had won.

MPP Vendors

Needed a common foundation to build a parallel SW industry

User Community

Fed-up recoding as they moved between platforms

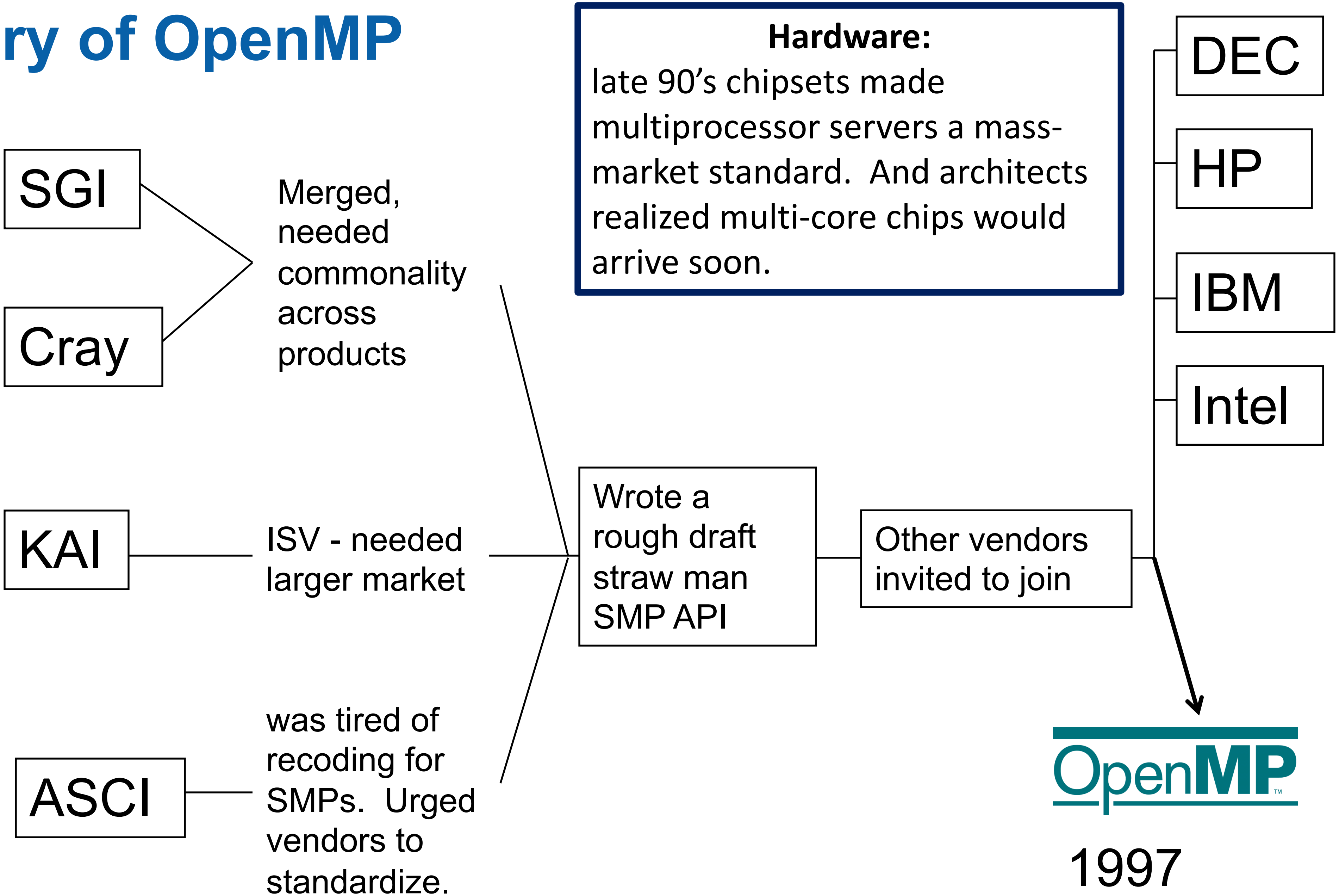
After several years of informal discussions, the MPI forum was created in 1992. A draft specification was presented one year later at SC'93.

MPI

1994

Many of us worked in the MPI forum … leadership came from the DOE National Labs. In particular, the reference implementation from Bill Gropp and Rusty Lusk of Argonne national lab called MPIch helped us get it right in the 1.0 specification and made sure a working implementation of the standard was available right from the beginning.

History of OpenMP



SGI

Cray

Merged, needed commonality across products

KAI

ISV - needed larger market

ASCI

was tired of recoding for SMPs. Urged vendors to standardize.

Wrote a rough draft straw man SMP API

Hardware:
late 90's chipsets made multiprocessor servers a mass-market standard. And architects realized multi-core chips would arrive soon.

Other vendors invited to join

DEC

HP

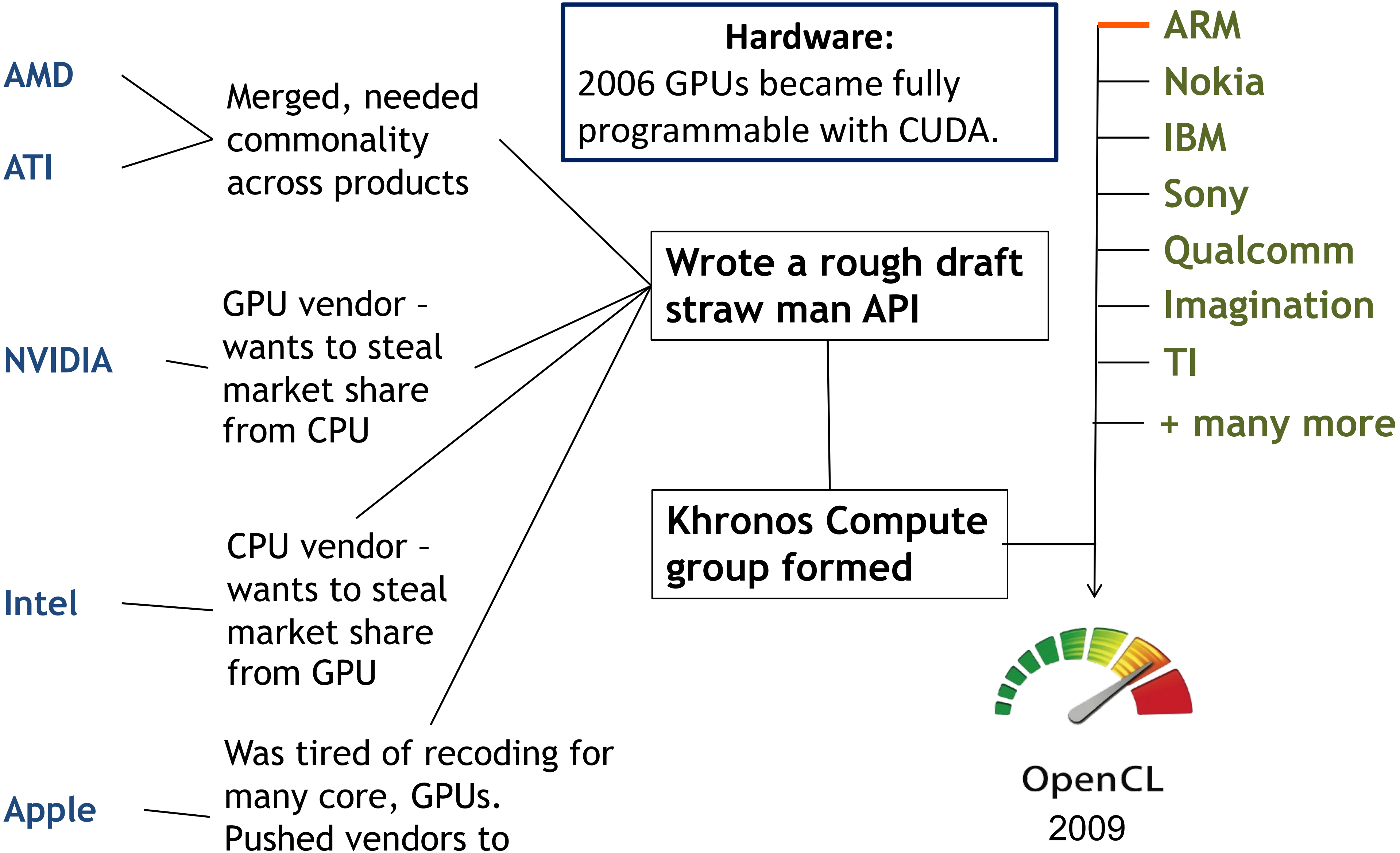
IBM

Intel

OpenMP

1997

The origins of OpenCL



AMD

ATI

Merged, needed commonality across products

NVIDIA

GPU vendor – wants to steal market share from CPU

Intel

CPU vendor – wants to steal market share from GPU

Apple

Was tired of recoding for many core, GPUs. Pushed vendors to standardize.

Hardware:
2006 GPUs became fully programmable with CUDA.

Wrote a rough draft straw man API

Khronos Compute group formed

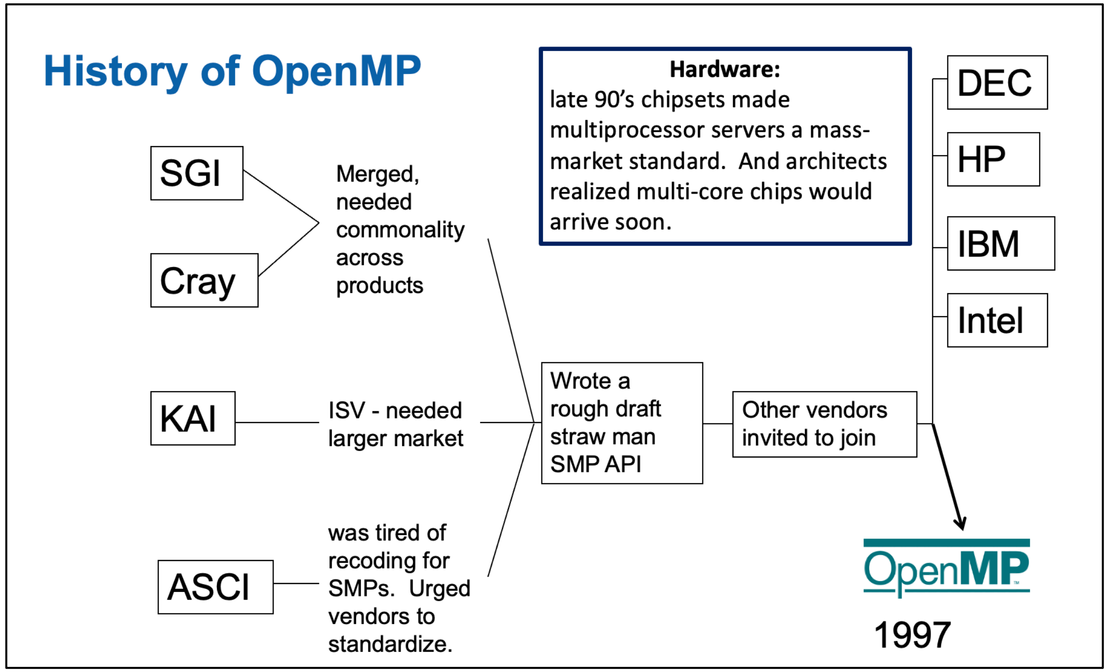
- ARM
- Nokia
- IBM
- Sony
- Qualcomm
- Imagination
- TI
- + many more

OpenCL
2009

Third party names are the property of their owners.

Key Lesson for you ….

- Application developers in HPC are the community that really matters …. You have MUCH MORE power than you think, but only:
  - You are willing to speak with One Voice.
  - You refuse to be trapped in a walled Garden.
  - Venders will try to divide and conquer you.   Hold firm or all is lost!



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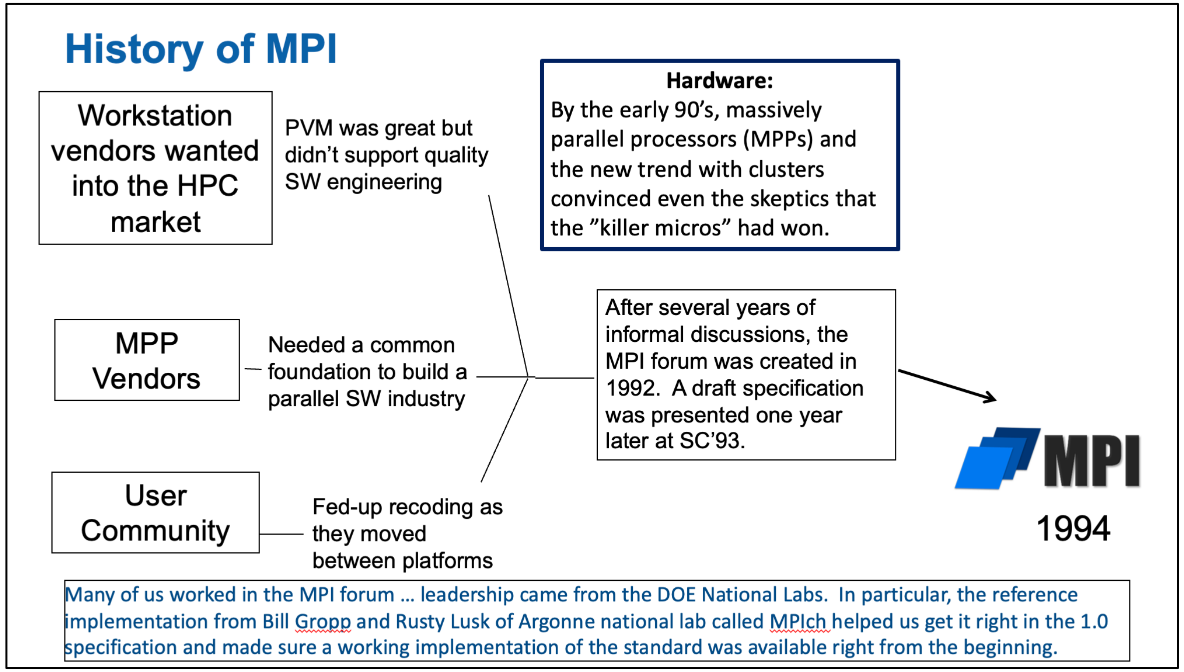

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BlockComm
C*.
"C* in C
C**
CarlOS
Cashmere
C4
CC++
Chu
Charlotte
Charm
Charm++
Cid
Cilk
CM-Fortran
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DOME
DOSMOS.
DRL
DSM-Threads
Filaments
FM
FLASH
The FORCE
Fork
Fortran-M
FX
GA
GAMMA
Glenda

GLU
GUARD
HAsL.
Haskell
HPC++
JAVAR.
HORUS
HPC
HPF
IMPACT
ISIS.
JAVAR
JADE
Java RMI
javaPG
JavaSpace
JIDL
Joyce
Khoros
Objective-Linda
LiPS
Locust
Lparx
Lucid
Maisie
Manifold

Mentat
Legion
Meta Chaos
Midway
Millipede
CparPar
Mirage
MpC
MOSIX
Modula-P
Modula-2*
Multipol
MPI
MPC++
Munin
Nano-Threads
PADE
PADRE
Panda
Papers
AFAPI.
Para++
Paradigm

Parafrase2
Paralation
Parallel-C++
Parallaxis
ParC
ParLib++
ParLin
Parmacs
Parti
pC
pC++
PCN
PCP:
PH
PEACE
PCU
PET
PETSc
PENNY
Quake
Quark
Quick Threads
Sage++
SCANDAL
SAM

pC++
SCHEDULE
SciTL
POET
SDDA.
SHMEM
SIMPLE
Sina
SISAL.
distributed smalltalk
SMI.
SONiC
Split-C.
SR
Sthreads
Strand.
SUIF.
Synergy
Telegrphos
SuperPascal
TCGMSG.
Threads.h++.
TreadMarks
TRAPPER
V
ViC*
Visifold V-NUS
VPE
Win32 threads
WinPar
WWWinda
XENOOPS
XPC
Zounds
ZPL

Please don't let this happen again


EVERYTIME YOU USE CUDA OR OPENACC
GOD KILLS A KITTEN
memegenerator.net

… Back to our previously scheduled program

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software
engineering

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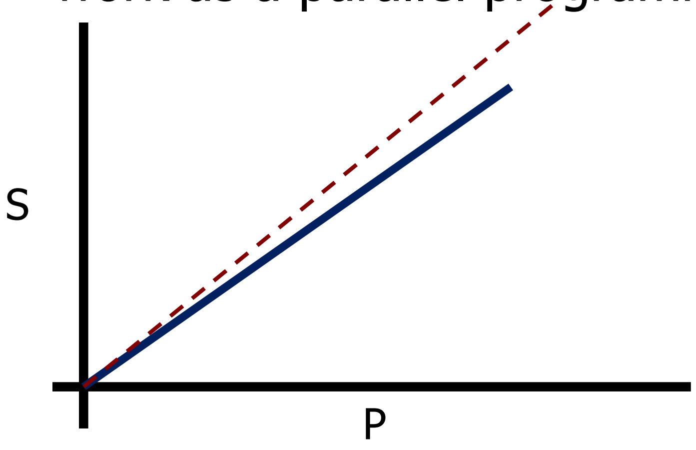
Introduction

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

Preliminaries

- Our plan for the day .. Active learning!
  - We will mix short lectures with short exercises.
  - You will use your laptop to connect to a multiprocessor server.
- Please follow these simple rules
  - Do the exercises that we assign and then change things around and experiment.
    - Embrace active learning!
  - Don't cheat: Do Not look at the solutions before you complete an exercise … even if you get really frustrated.

Download tutorial materials onto your laptop:
git clone https://github.com/tgmattso/ATPESC.git

Preliminaries: Using Polarisa for exercises

Start an interactive job on one node

```
% qsub -I -l select=1 -l walltime=00:30:00 -l filesystems=home:eagle -A ATPESC2025 -q ATPESC

% module li                                   ← to see which modules are loaded
% cc –v                                       ← to see which compiler cc wraps
% module swap PrgEnv-nvhpc PrgEnv-gnu         ← change from the Nvidia programming environment to gnu

% gcc -fopenmp -O3  pi_loop.c      ← compile for a CPU.  On Polaris, the O3 was needed for good results
% ./a.out

% module swap PrgEnv-nvhpc PrgEnv-gnu         ← change back to Nvidia programming environment
% cc –mp heat_map_target.c.
% OMP_TARGET_OFFLOAD=MANDATORY ./a.out.  ← might be needed for tiny programs
```

Use homebrew to install gnu compilers on your Apple laptop

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

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

- Go to the homebrew web site (brew.sh). Cut and paste the command near the top of the page to install homebrew (in /opt/homebrew):

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

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

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

- Install the latest gcc compiler

```
% brew install gcc
```

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

```
% gcc-13 –fopenmp hello.c
```

OpenMP Compilers on Apple Laptops: MacPorts

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

But if you prefer MacPorts, this procedure should work.

- To use OpenMP on your Apple laptop:
- Download Xcode. Be sure to choose the command line tools 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 gcc13`	Grab version 13 gnu compilers (5-10 mins)
`port select --list gcc`	List versions of gcc on your system
`sudo port select --set gcc mp-gcc13`	Select the mp enabled version of the most recent gcc release
`gcc –fopenmp hello.c`	Test the installation with a simple program

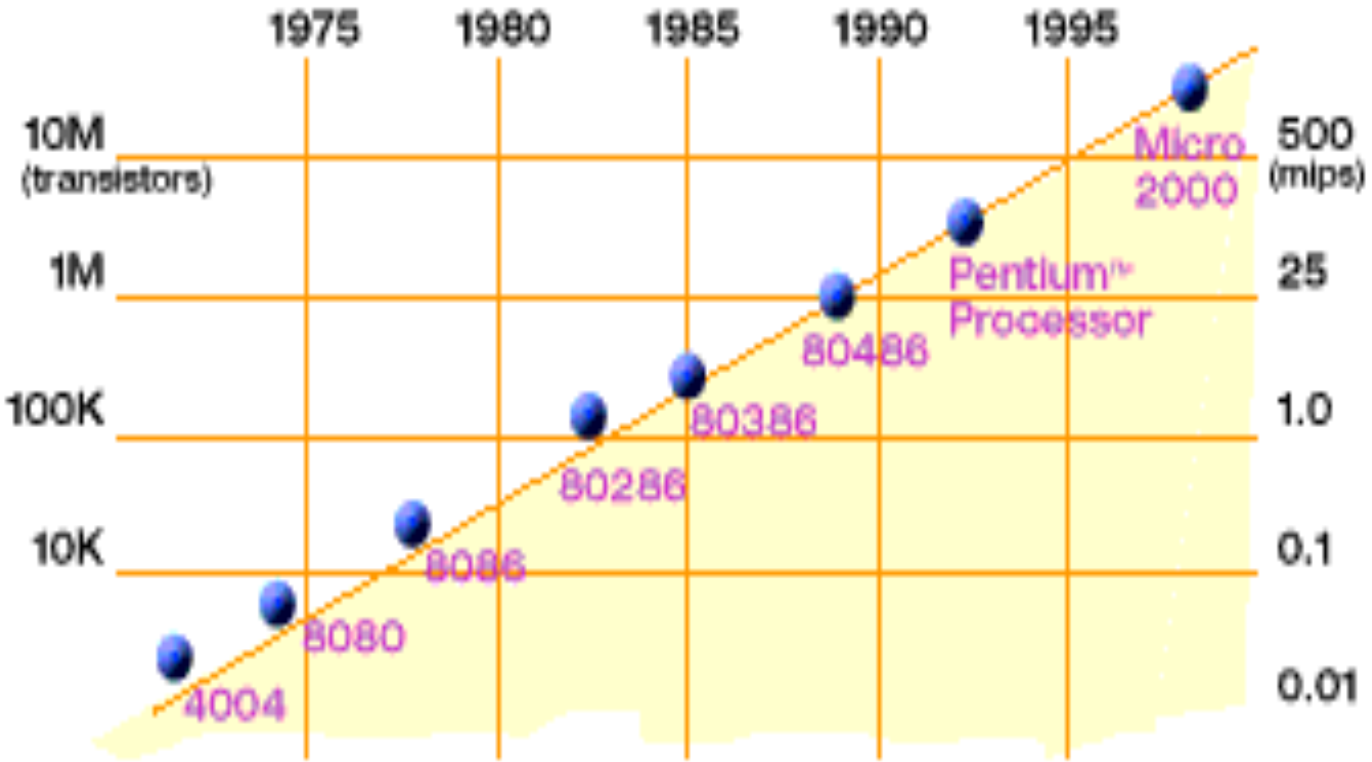
Download tutorial materials onto your laptop:
git clone https://github.com/tgmattso/ATPESC.git

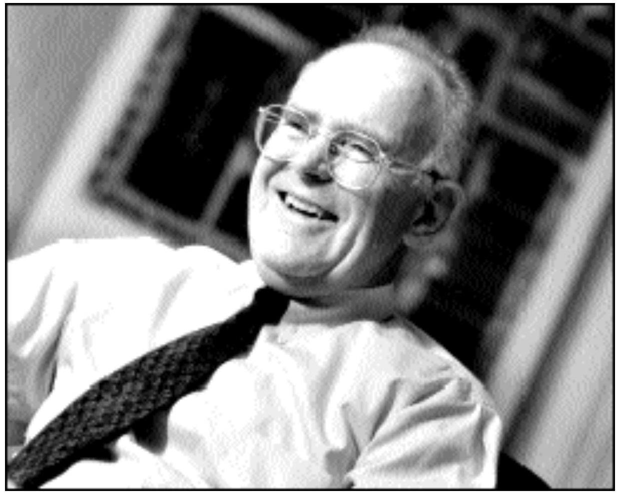
Plan for the OpenMP sessions

Note: How much time people need with the exercises never works out as I expect, which is fine. Everything is driven by the needs of the students … not some concept I might have of a schedule.

Monday, PM	4:00	Introduction: Parallel programming and the OpenMP Common Core
	4:30	Working with threads (Including synchronization): the SPMD Pattern
	5:30	Worksharing and data sharing: The Loop Parallelism Pattern
	~6:30	Dinner
	Next Day	
Tuesday, All Day	8:30	Task-level parallelism in OpenMP: The Divide and Conquer Pattern
	10:00	Break
	10:30	Beyond the common core: More Worksharing and synchronization … plus threadprivate
	12:30	Lunch
	1:30	Wrapping up the CPU and transitioning to GPU-programming
	2:30	The loop construct … GPU programming made “simple”
	3:30	Break
	4:00	Explicit Data Movement and basic principles of GPU optimization
	5:30	Detailed control of the GPU … and comparisons to other GPU programming models
	6:30	Dinner

Moore's Law



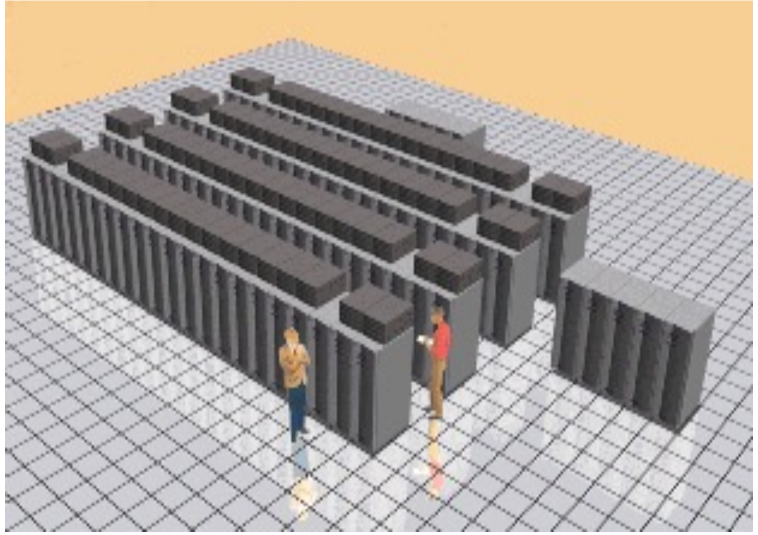


- In 1965, Intel co-founder Gordon Moore predicted (from just 3 data points!) that semiconductor density would double every 18 months.
  - ***He was right!*** Over the last 50 years, transistor densities have increased as he predicted.

Slide source: UCB CS 194 Fall’2010

Moore's Law: A personal perspective

First TeraScale* computer: 1997



Intel's ASCI Option Red

Intel's ASCI Red Supercomputer

9000 CPUs

one megawatt of electricity.

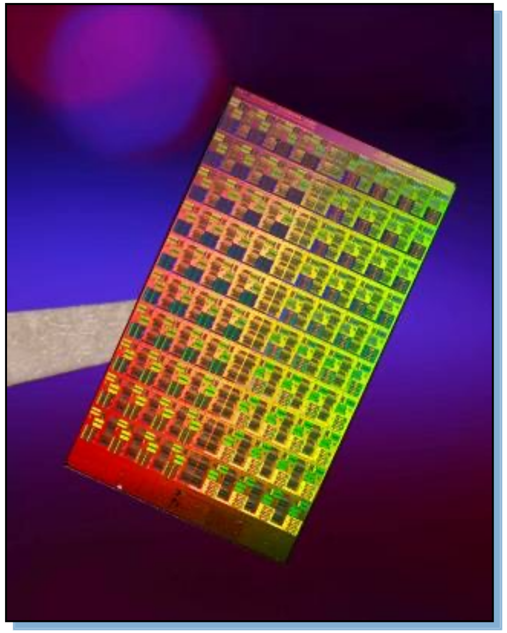
1600 square feet of floor space.

*Double Precision TFLOPS running MP-Linpack

A TeraFLOP in 1996: The ASCI TeraFLOP Supercomputer, Proceedings of the International Parallel Processing Symposium (1996), T.G. Mattson, D. Scott and S. Wheat.

10 years later

First TeraScale% chip: 2007



Intel's 80 core teraScale Chip

1 CPU

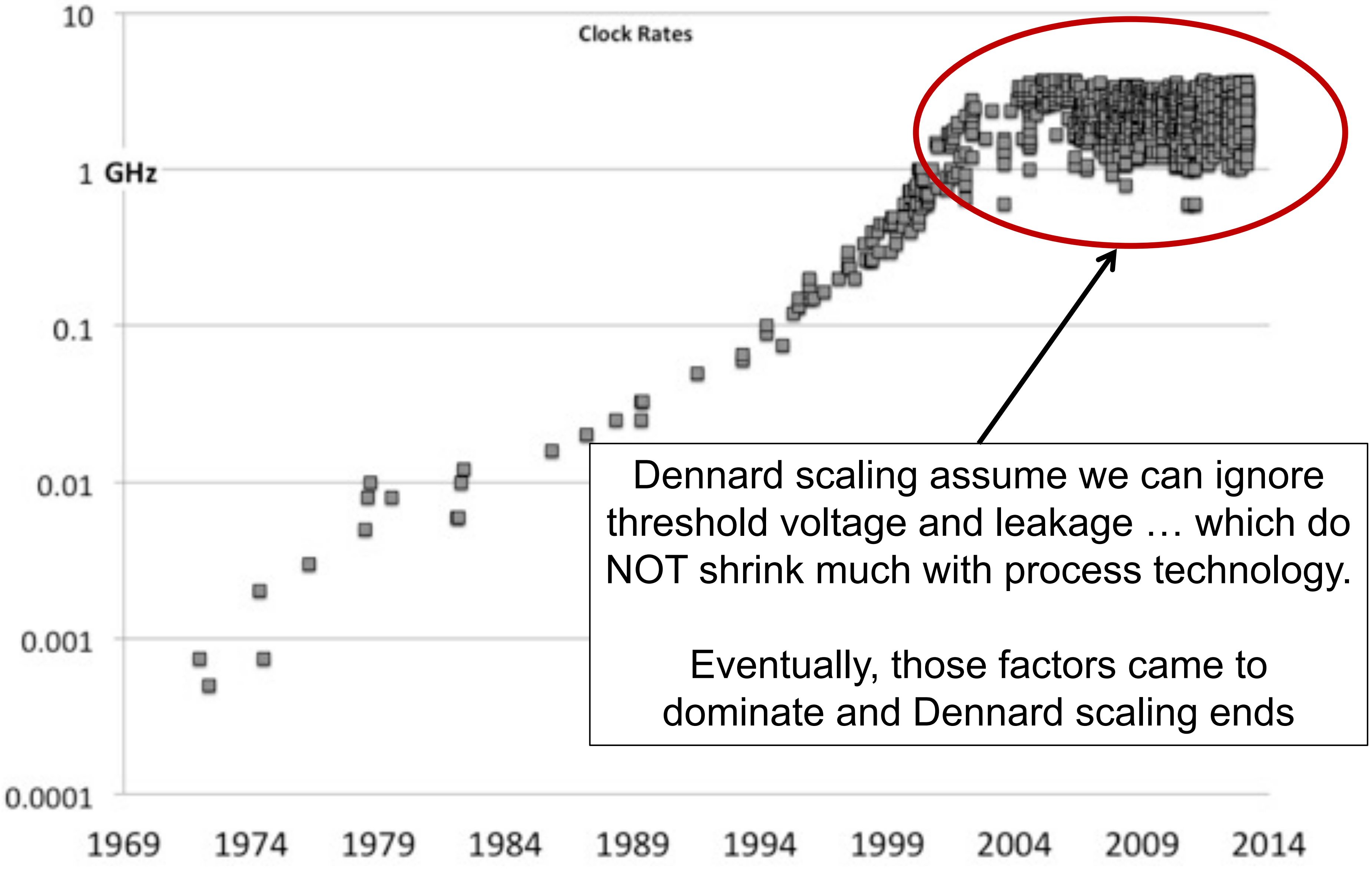
97 watt

275 mm2

%Single Precision TFLOPS running stencil

Programming Intel's 80 core terascale processor
SC08, Austin Texas, Nov. 2008, Tim Mattson, Rob van der Wijngaart, Michael Frumkin

CPU Frequency (GHz) over time (years)

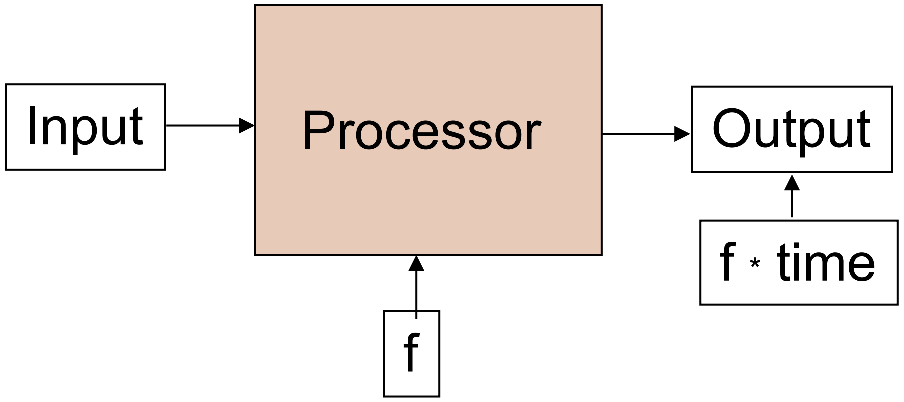


Dennard scaling assume we can ignore threshold voltage and leakage … which do NOT shrink much with process technology.

Eventually, those factors came to dominate and Dennard scaling ends

Source: James Reinders (from the book “structured parallel programming”)

Consider power in a chip …



Capacitance = C
Voltage = V
Frequency = f
Power = CV^2f

C = capacitance … it measures the ability of a circuit to store energy:

$$C = q/V \rightarrow \quad q = CV$$

Work is pushing something (charge or q) across a "distance" … in electrostatic terms pushing q from 0 to V:

$$V * q = W.$$

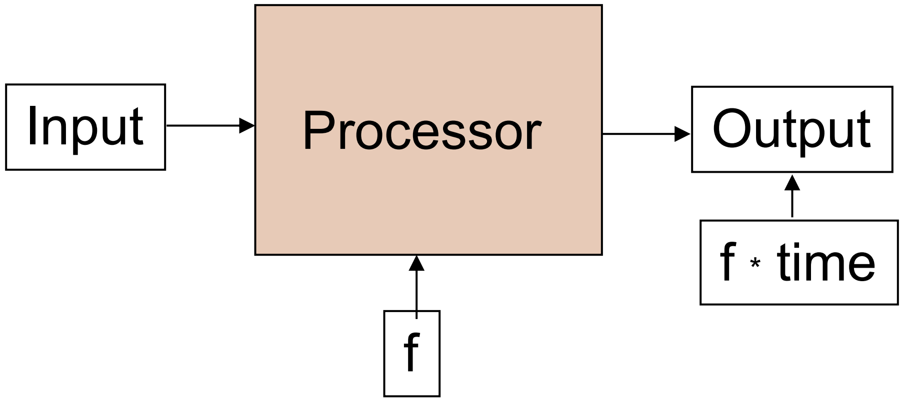
But for a circuit $q = CV$ so

$$W = CV^2$$

power is work over time … or how many times per second we oscillate the circuit

$$\text{Power} = W^* F \quad \rightarrow \quad \text{Power} = CV^2f$$

... Reduce power by adding cores



Input

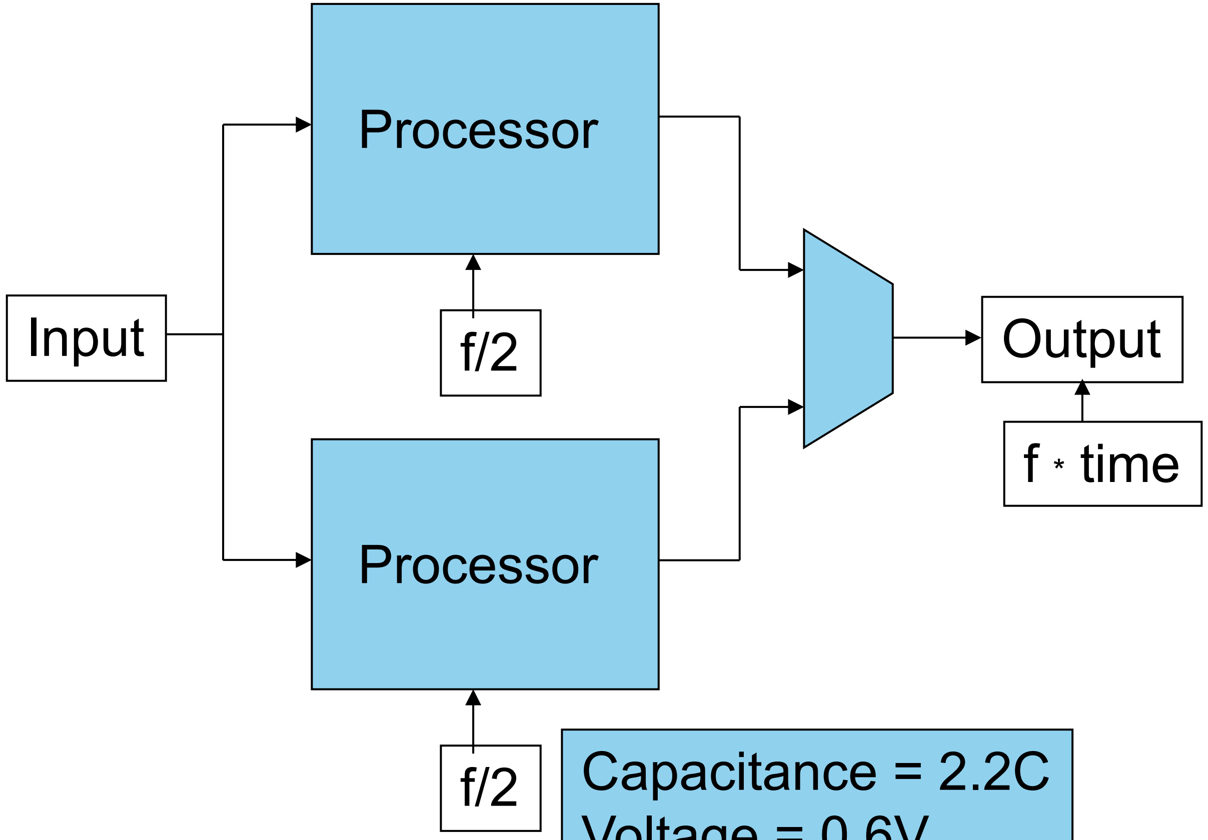
Processor

Output

f

f * time

Capacitance = C
Voltage = V
Frequency = f
Power = CV^2f



Input

Processor

f/2

Processor

f/2

Output

f * time

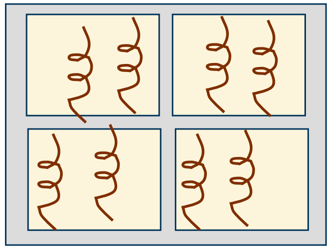
Capacitance = 2.2C
Voltage = 0.6V
Frequency = 0.5f
Power = $0.396CV^2f$

Chandrakasan, A.P.; Potkonjak, M.; Mehra, R.; Rabaey, J.; Brodersen, R.W., "Optimizing power using transformations," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems,*, vol.14, no.1, pp.12-31, Jan 1995

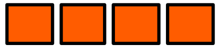
Source: Vishwani Agrawal

For hardware … parallelism is the path to performance

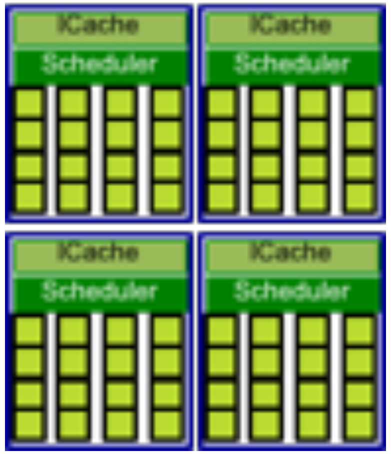
All hardware vendors are in the game … parallelism is ubiquitous so if you care about getting the most from your hardware, you will need to create parallel software.



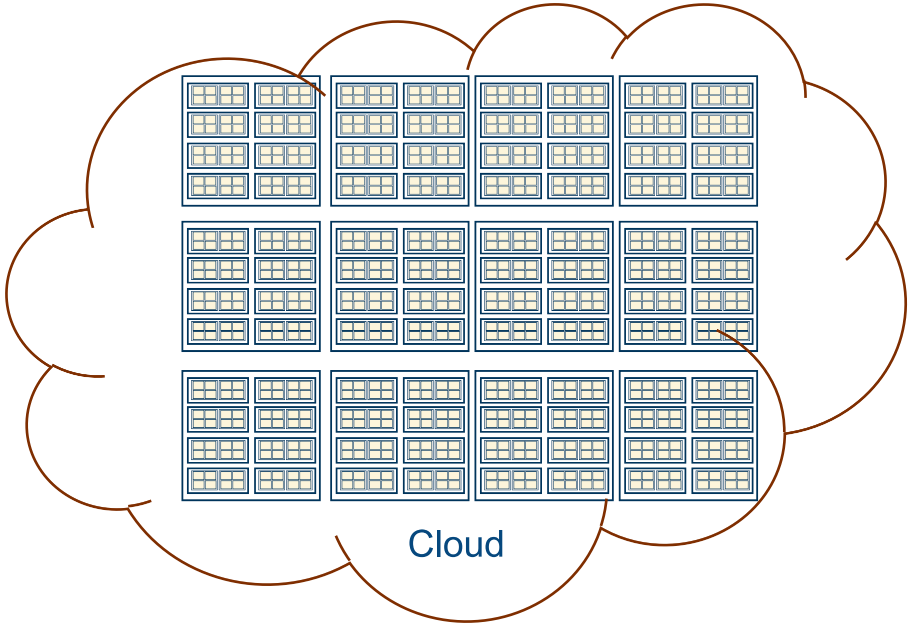
CPU



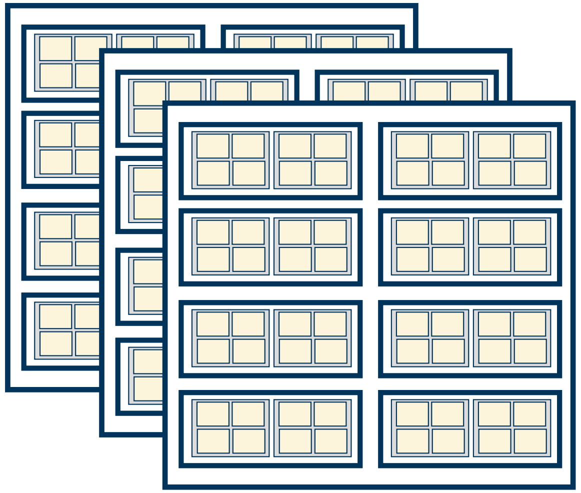
SIMD/Vector



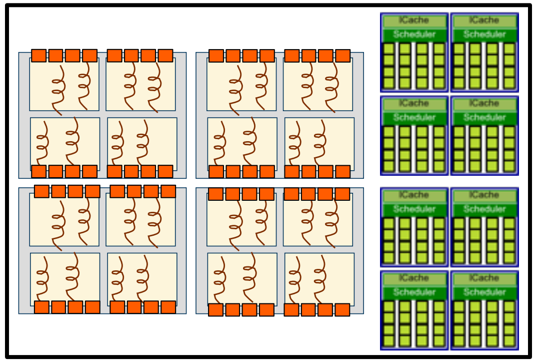
GPU



Cloud



Cluster



Heterogeneous node

The best way to master parallel computing …

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

… and the simplest API for parallelism is?

Outline

- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- Memory Model
- Irregular Parallelism and Tasks
- Worksharing Revisited
- Synchronization Revisited: Options for Mutual exclusion
- Threadprivate and the joys of “random” numbers
- Recap

OpenMP* Overview

`C$OMP FLUSH` `#pragma omp critical` `#pragma omp single`

`C$OMP THREADPRIVATE(/ABC/)` `C$OMP ATOMIC` `CALL OMP_SET_NUM_THREADS(10)`

`cal`

`C$O` `ED`

OpenMP: An API for Writing Parallel Applications

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

`#pragma omp parallel for private(A, B)` `C$OMP PARALLEL REDUCTION (+: A, B)`

`C$OMP PARALLEL COPYIN(/blk/)` `C$OMP DO lastprivate(XX)` `#pragma omp atomic seq_cst`

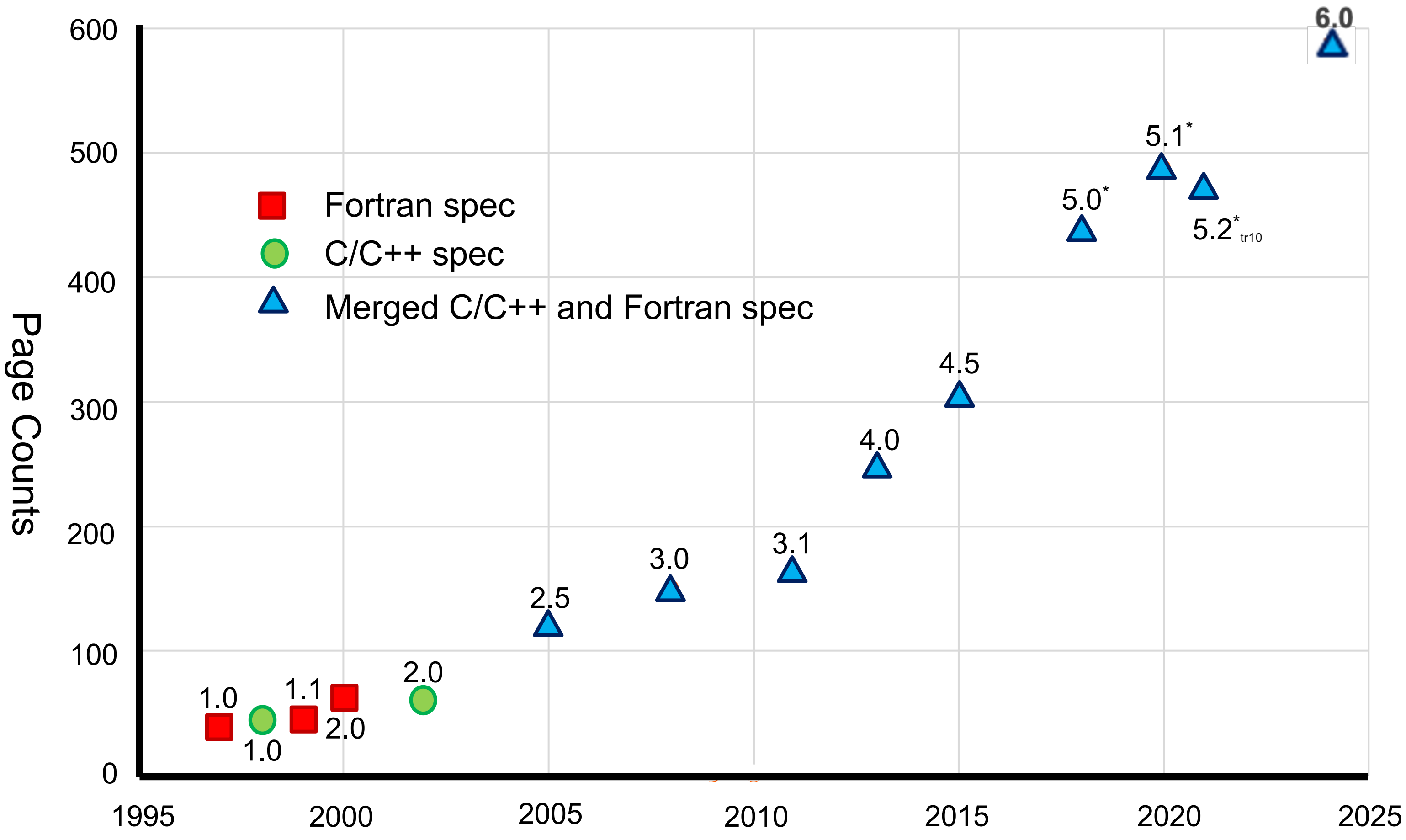
`Nthrds = OMP_GET_NUM_PROCS()` `omp_set_lock(lck)`

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

The Growth of Complexity in OpenMP

Our goal in 1997 … A simple interface for application programmers

Page Counts … not including front matter, tools-interface, appendices or the index.

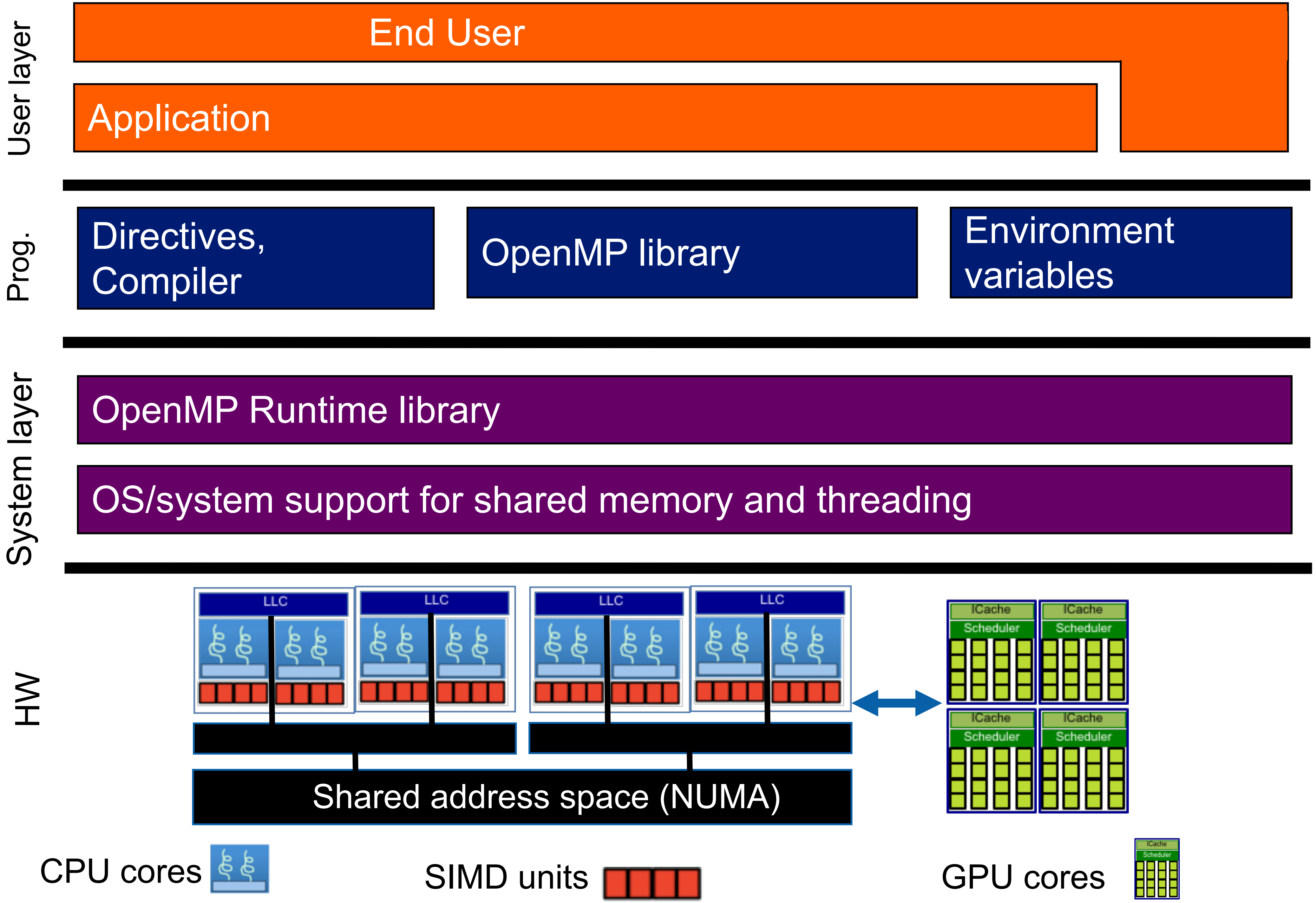


The OpenMP specification is so long and complex that few (if any) humans understand the full document

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



User layer

End User

Application

Prog.

Directives, Compiler

OpenMP library

Environment variables

System layer

OpenMP Runtime library

OS/system support for shared memory and threading

HW

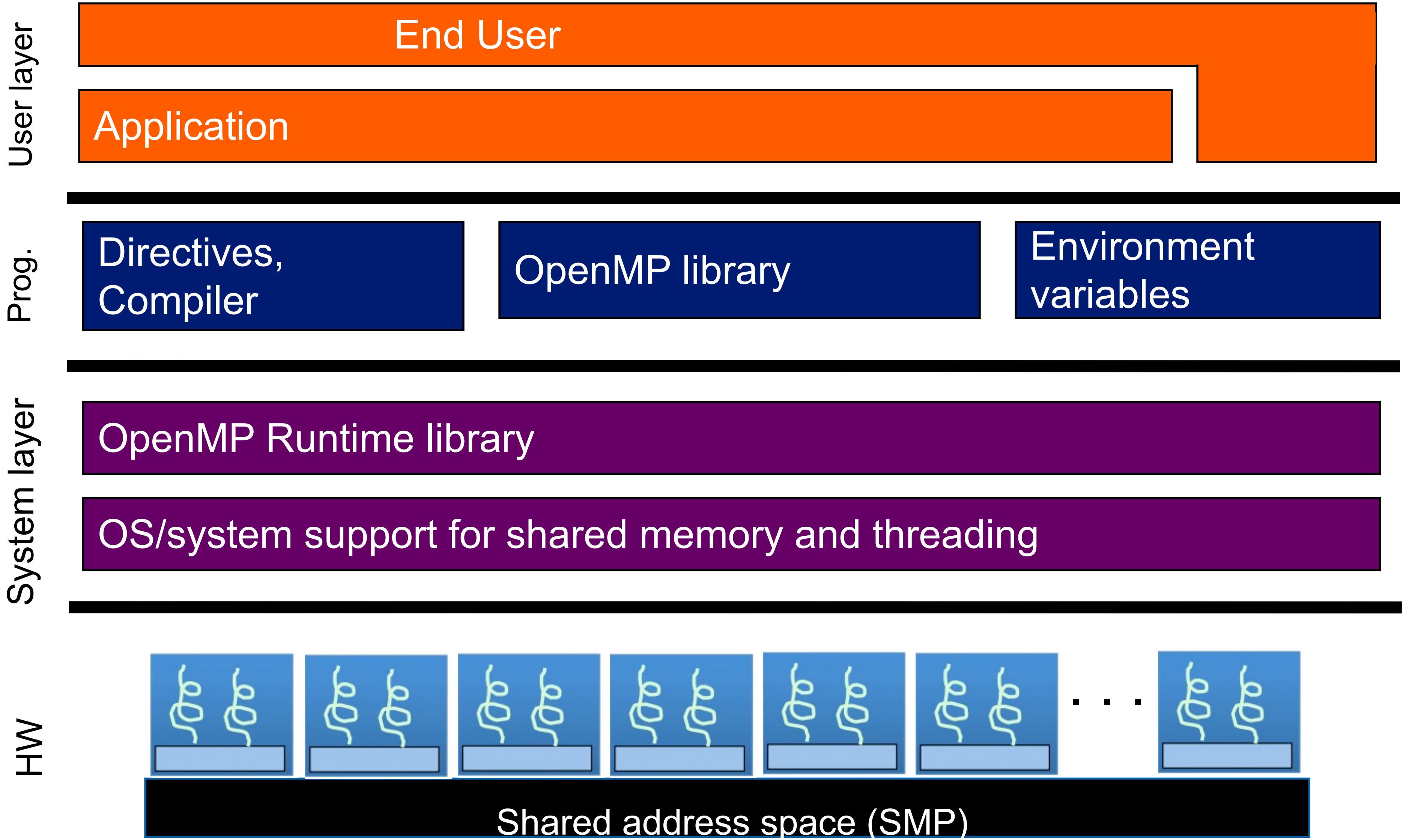
Shared address space (NUMA)

CPU cores

SIMD units

GPU cores

OpenMP Basic Definitions: Basic Solution Stack



User layer

End User

Application

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Directives, Compiler

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Environment variables

System layer

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OS/system support for shared memory and threading

HW

. . .

Shared address space (SMP)

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.

<table>
<tr><th>C and C++</th><th>Fortran</th></tr>
<tr><td colspan="2">Compiler directives</td></tr>
<tr><td><i>#pragma omp construct [clause [clause]…]</i></td><td><i>!$OMP construct [clause [clause] …]</i></td></tr>
<tr><td colspan="2">Example</td></tr>
<tr><td><i>#pragma omp parallel private(x)</i>
<i>{</i>
<i>}</i></td><td><i>!$OMP PARALLEL PRIVATE(X)</i>
<i>!$OMP END PARALLEL</i></td></tr>
<tr><td colspan="2">Function prototypes and types:</td></tr>
<tr><td><i>#include <omp.h></i></td><td><i>use OMP_LIB</i></td></tr>
</table>

- 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”);

}
```

```
qsub -I -l select=1 -l walltime=00:30:00 -l filesystems=home:eagle -A ATPESC2025 -q ATPESC
module swap PrgEnv-nvhpc PrgEnv-gnu     ← change from the Nvidia programming environment to gnu
gcc -fopenmp -O3  pi_loop.c     ← compile for a CPU.  On Polaris, the O3 was needed for good results
```

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 –O3
```

-O3 isn’t usually needed, but on Polaris, it is important for good scaling

Solution

A Multi-Threaded “Hello World” Program

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

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


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

OpenMP include file

Parallel region with default number of threads

End of the Parallel region

Sample Output:

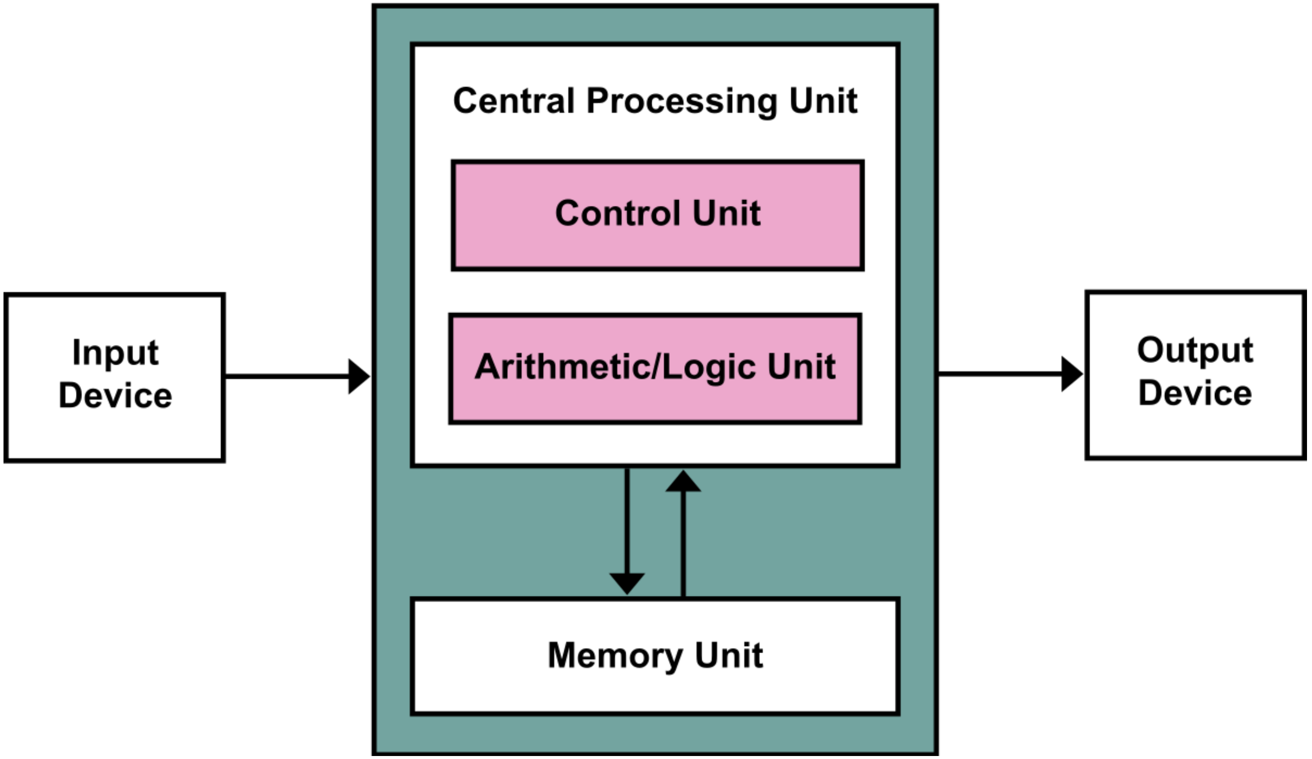
```
hello hello world
world
hello  hello world
world
```

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

A brief digression on the terminology of parallel computing

Let’s agree on a few definitions:

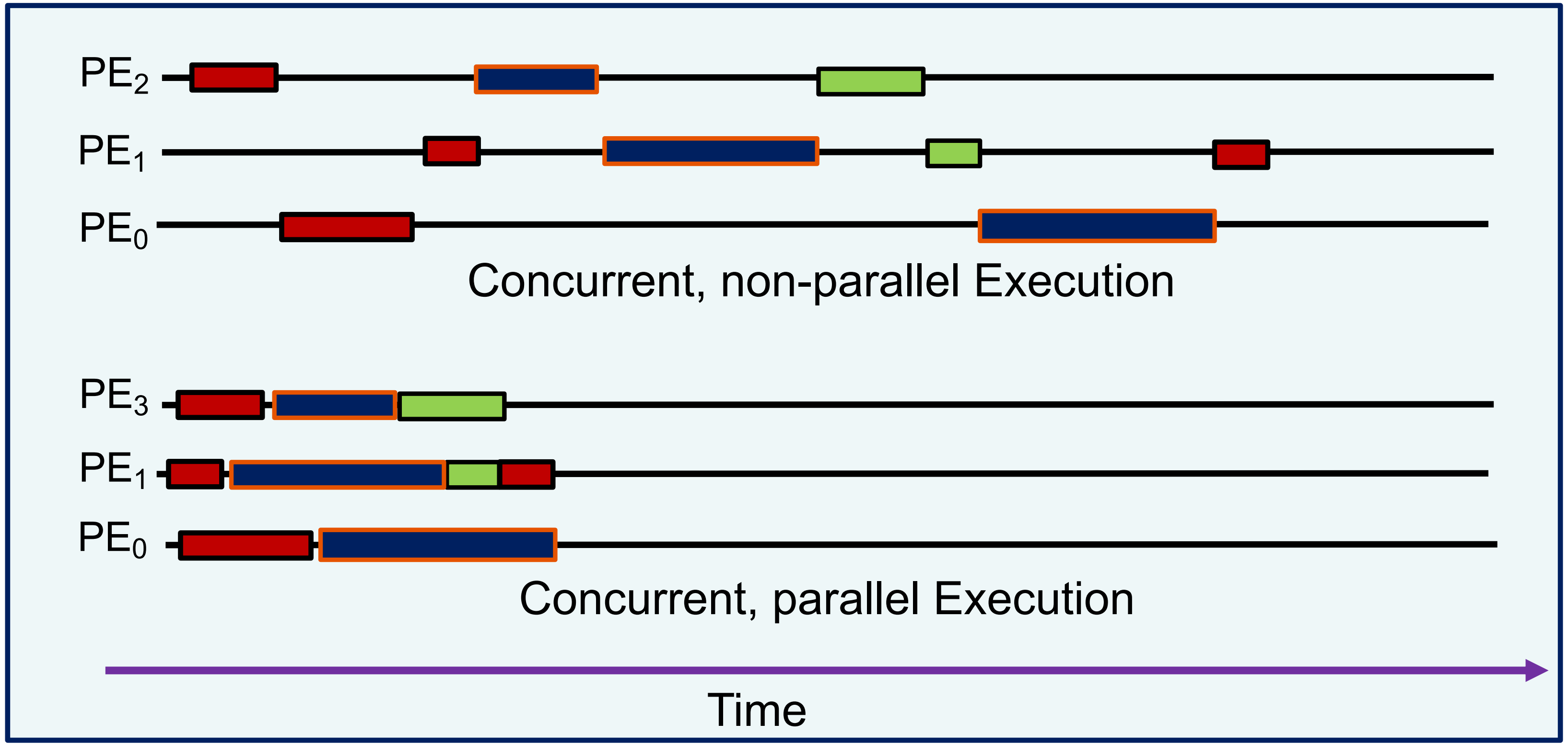
- **Computer:**
  - A machine that transforms *input values* into *output values*.
  - Typically, a computer consists of Control, Arithmetic/Logic, and Memory units.
  - The transformation is defined by a stored **program** (von Neumann architecture).



- **Task:**
  - A sequence of instructions plus a data environment. A program is composed of one or more tasks.
- **Active task:**
  - A task that is available to be scheduled for execution. When the task is moving through its sequence of instructions, we say it is making **forward progress**
- **Fair scheduling:**
  - When a scheduler gives each active task an equal *opportunity* for execution.

Concurrency vs. Parallelism

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

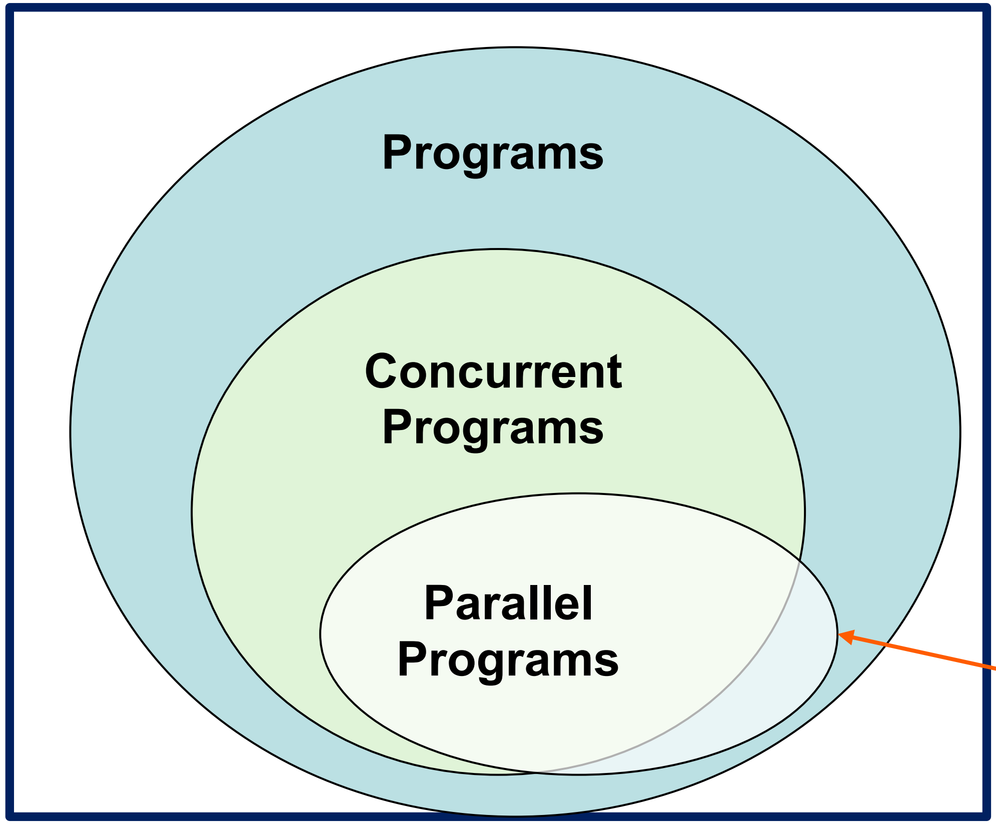


PE = Processing Element

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

Concurrency vs. Parallelism

- 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.



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

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

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

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

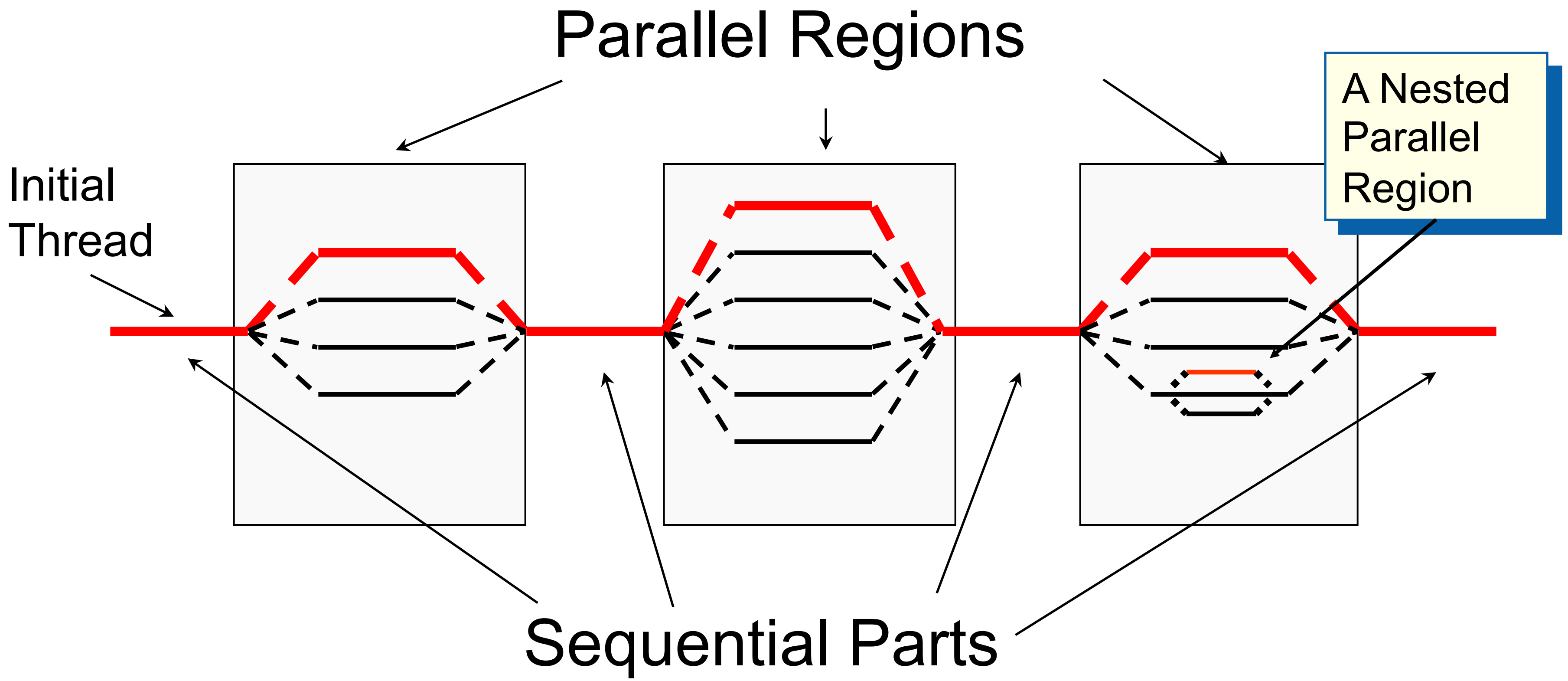
Outline

- Introduction to OpenMP
- ➡ Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- Memory Model
- Irregular Parallelism and Tasks
- Worksharing Revisited
- Synchronization Revisited: Options for Mutual exclusion
- Threadprivate and the joys of “random” numbers
- Recap

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

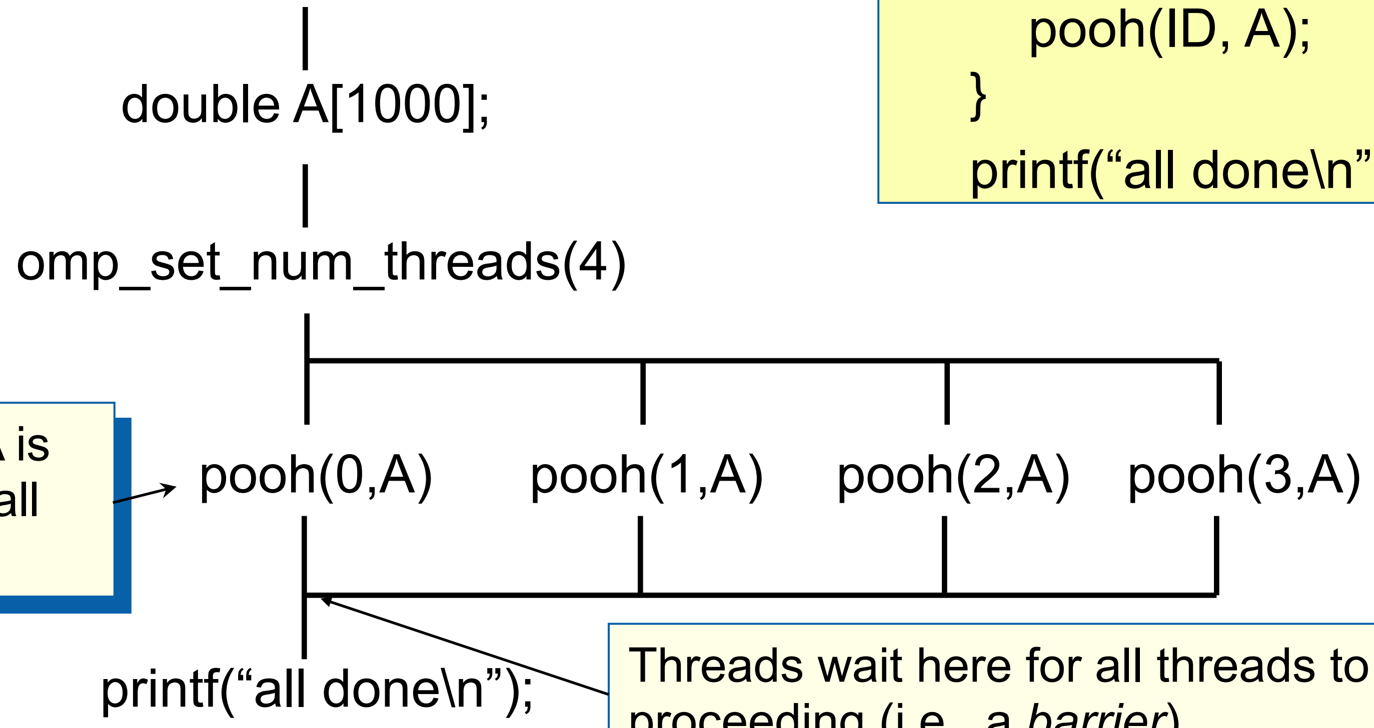
Runtime function returning a thread ID

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

Thread Creation: Parallel Regions Example

- Each thread executes the same code redundantly.

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



A single copy of A is shared between all threads.

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

Thread creation: How many threads did you actually get?

- Request a number of threads with omp_set_num_threads()

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

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

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

        int nthrds = omp_get_num_threads();
        pooh(ID,A);
}
```

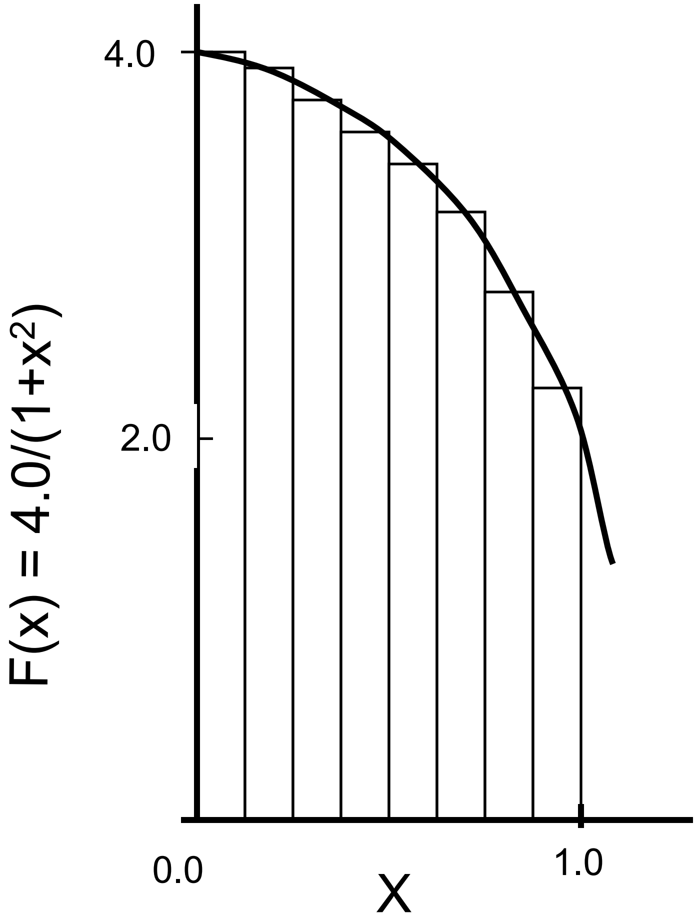
Runtime function to request a certain number of threads

Runtime function to return actual number of threads in the team

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

An Interesting Problem to Play With

Numerical Integration



Mathematically, we know that:

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

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

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

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

Serial PI Program

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

            step = 1.0/(double) num_steps;

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

See ParProgForPhys/OMP_Exercises/pi.c

Serial PI Program

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

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

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

See `ATPESC/OMP_Exercises/pi.c`

Exercise: the Parallel Pi Program

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

  #pragma omp parallel

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

Number of threads in the team

Thread ID or rank

Time in seconds since a fixed point in the past

Request a number of threads in the team

git clone https://github.com/tgmattso/ATPESC.git

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

*SPMD: Single Program Multiple Data

Example: A simple SPMD pi program … an alternative solution

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

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

SPMD: Single Program Multiple Data

Results*

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

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

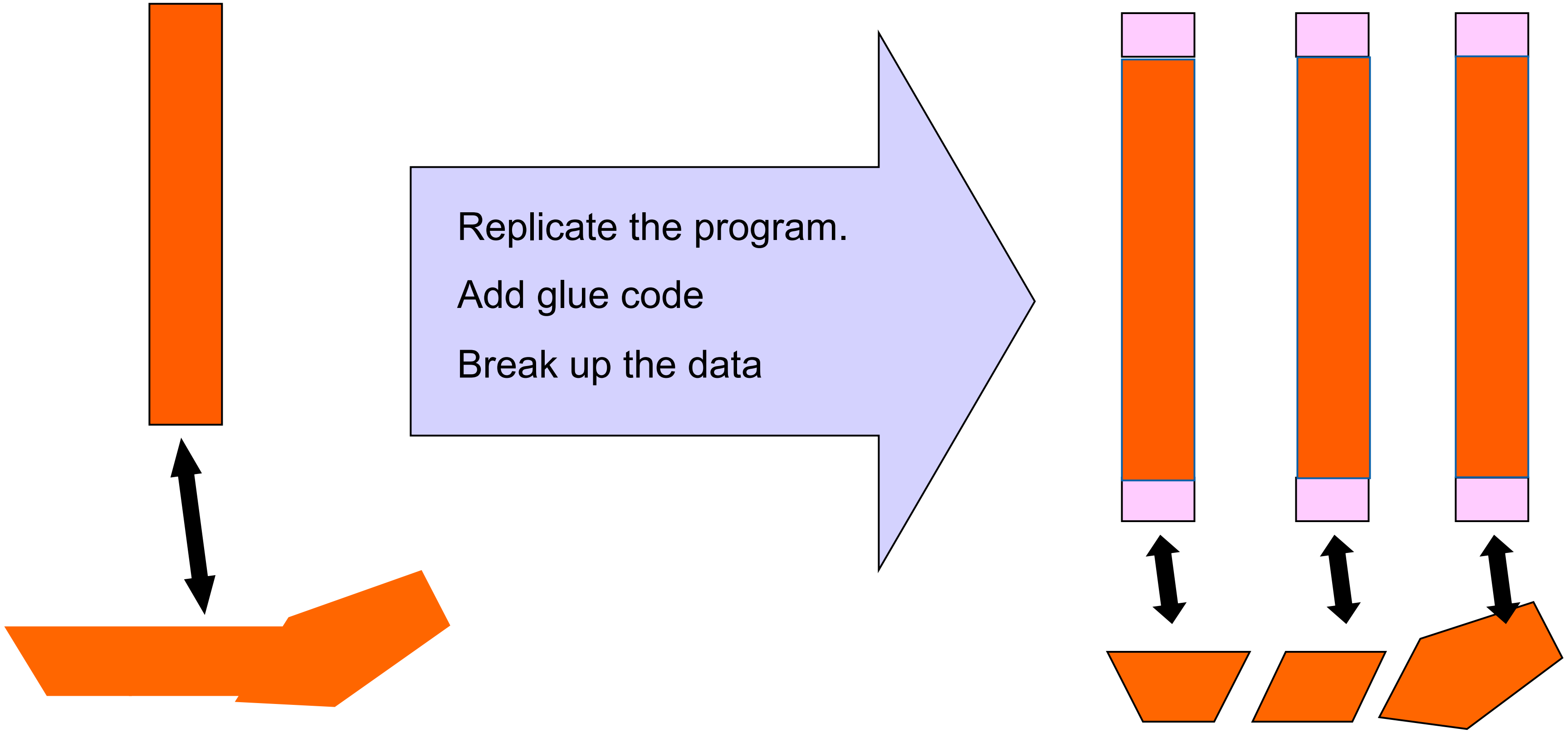
threads	1st SPMD*
1	1.86
2	1.03
3	1.08
4	0.97

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

*SPMD: Single Program Multiple Data

SPMD: Single Program Multiple Data

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



Replicate the program.

Add glue code

Break up the data

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

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

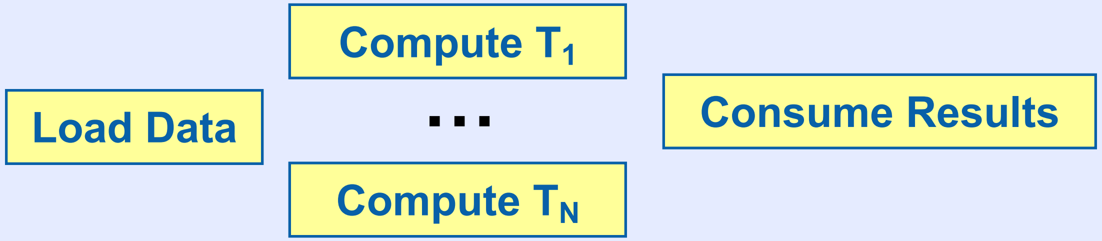
A brief digression to talk about performance issues in parallel programs

Consider performance of parallel programs

Compute N independent tasks on one processor

$$\text{Time}_{seq}(1) = T_{load} + N*T_{task} + T_{consume}$$

Compute N independent tasks with P processors



$$\text{Time}_{par}(P) = T_{load} + (N/P)*T_{task} + T_{consume}$$

Ideally Cut runtime by ~1/P

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

Talking about performance

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

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

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

$$S(P) = P$$

- Efficiency: How well does your observed speedup compare to the ideal case?

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

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.

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

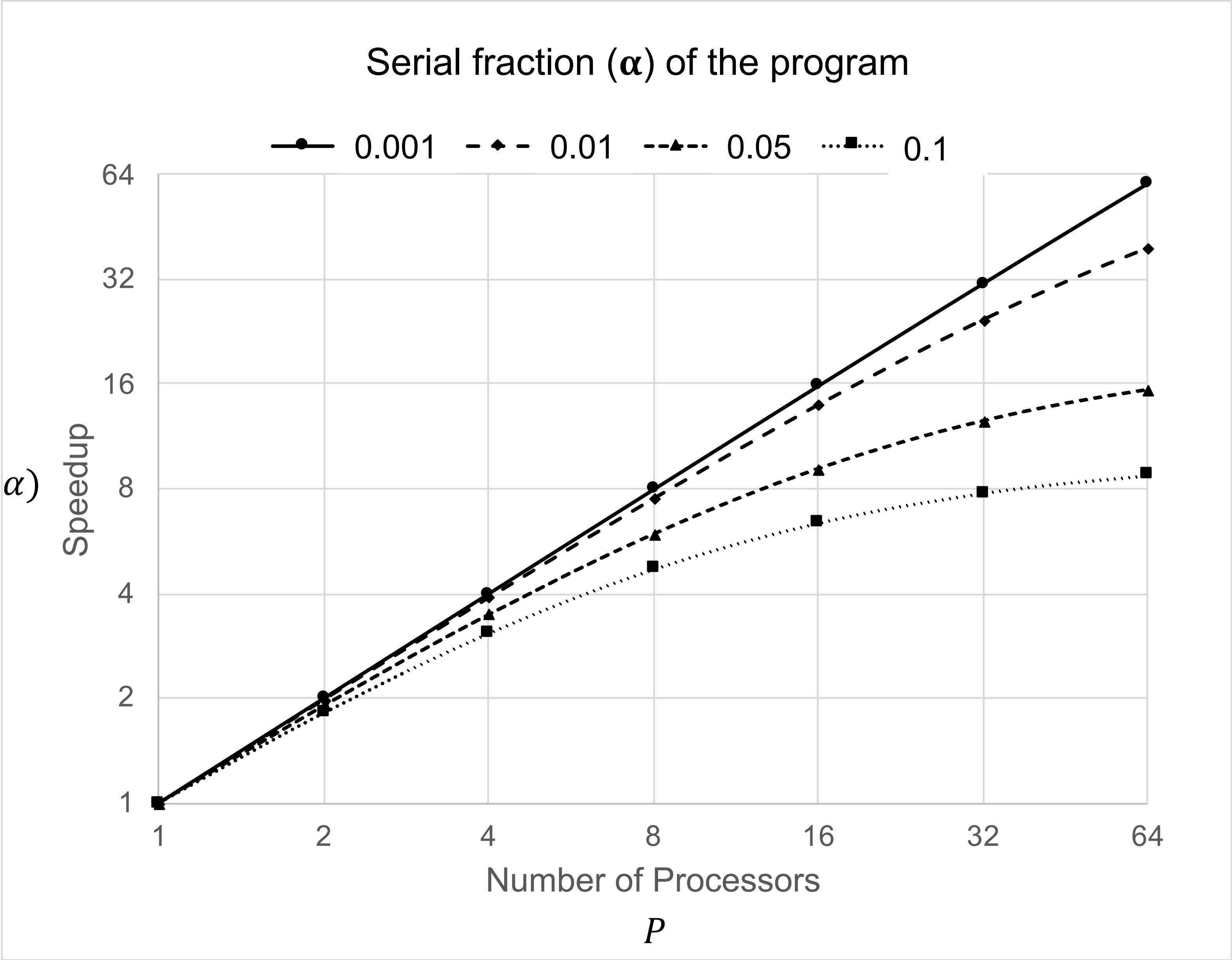
- If the serial fraction is α and the parallel fraction is $(1-\alpha)$ then the speedup is:

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

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

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

Amdahl’s Law … It’s not just about the maximum speedup

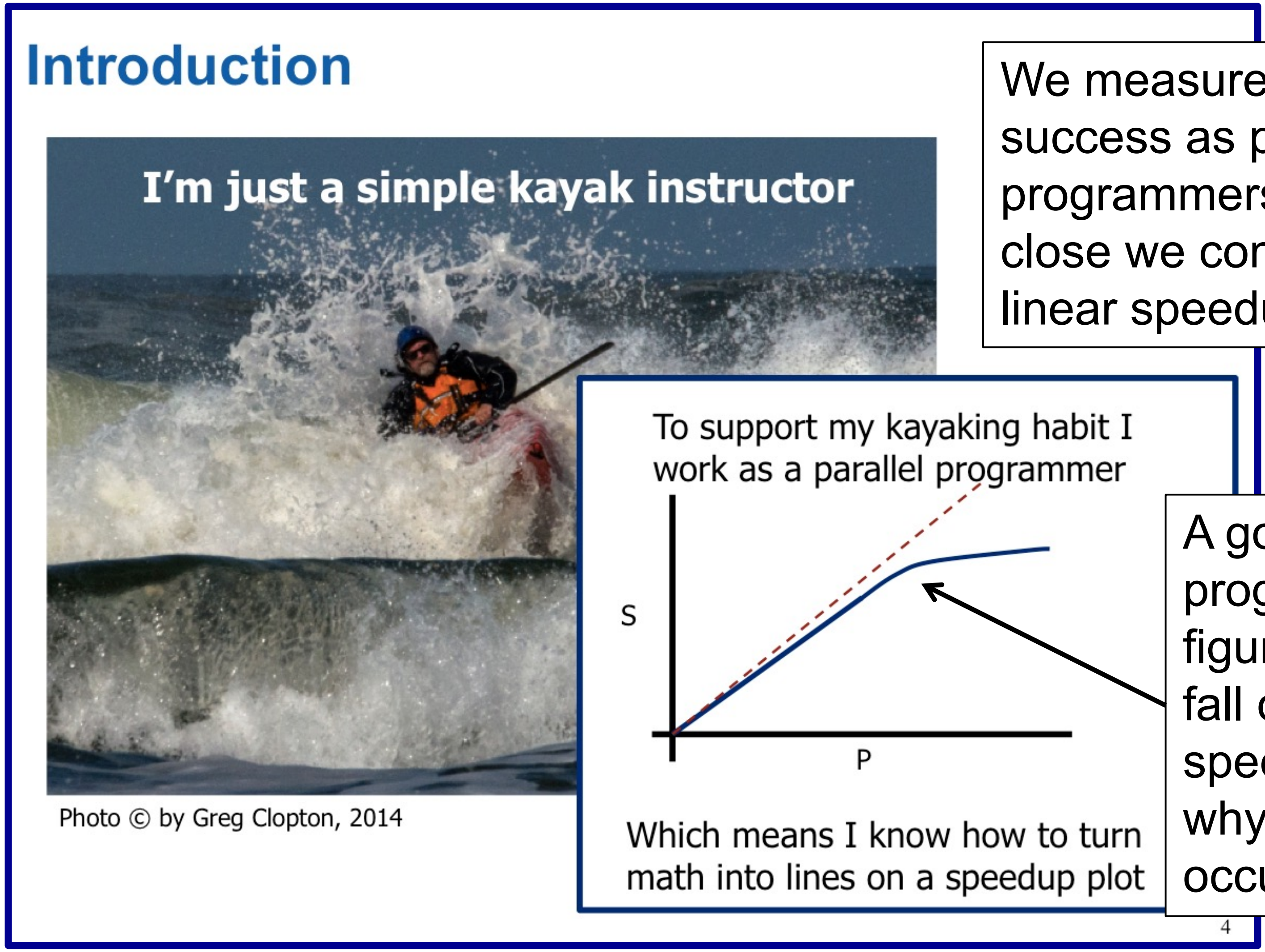


$S(P, \alpha)$

P

$$S(P, \alpha) = \frac{1}{\alpha - \frac{1 - \alpha}{P}}$$

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.

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;
}
```

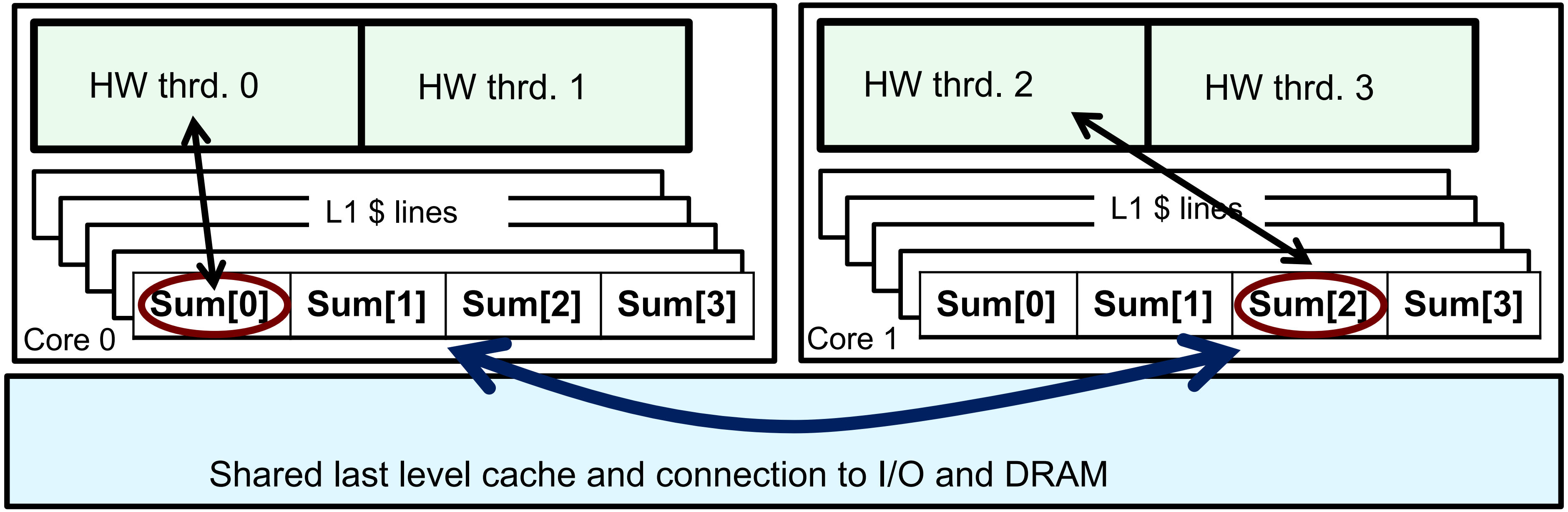
threads	1st SPMD*
1	1.86
2	1.03
3	1.08
4	0.97

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

*SPMD: Single Program Multiple Data

Why Such Poor Scaling? False Sharing

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



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

Example: Eliminate false sharing by padding the sum array

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

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

Results*: PI Program, Padded Accumulator

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

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

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

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

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- Threadprivate and the joys of “random” numbers
- Recap

Synchronization

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

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

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

Synchronization: critical

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

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

```
float  res;

#pragma omp parallel

{     float B;   int i, id, nthrds;

      id = omp_get_thread_num();

      nthrds = omp_get_num_threads();

      B =  big_SPMD_job(id, nthrds);

      #pragma omp critical
            res += consume (B);


}
```

Synchronization: barrier

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

```
double Arr[8], Brr[8];          int numthrds;
omp_set_num_threads(8)
#pragma omp parallel
{   int id, nthrds;
     id = omp_get_thread_num();
     nthrds = omp_get_num_threads();
     if (id==0) numthrds = nthrds;
     Arr[id] = big_ugly_calc(id, nthrds);
#pragma omp barrier
     Brr[id] = really_big_and_ugly(id, nthrds, Arr);
}
```

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

Exercise

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

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

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

PI Program with False Sharing

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

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

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

threads	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^{TM} i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

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

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

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

No array, so no false sharing.

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

Results*: pi program critical section

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

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

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

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core^{TM} 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];}
```

Loop Worksharing Constructs: The schedule clause

- The schedule clause affects how loop iterations are mapped onto threads
  - **schedule(static [,chunk])**
    - Deal-out blocks of iterations of size “chunk” to each thread.

  - **schedule(dynamic[,chunk])**
    - Each thread grabs “chunk” iterations off a queue until all iterations have been handled.
- Example:
  - #pragma omp for schedule(dynamic, 10)

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

Least work at runtime : scheduling done at compile-time

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

Combined Parallel/Worksharing Construct

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

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

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

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

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

Remove loop carried dependence

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
-	0
min	Largest pos. number
max	Most neg. number

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

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

OpenMP includes user defined reductions 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>
void main ()
{
    long num_steps = 100000;
    double pi, sum = 0.0;
    double 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;
}
```

Results*: PI with a loop and a reduction

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

Example: PI with a loop and a reduction

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

threads	1st SPMD	1st SPMD padded	SPMD critical	PI Loop
1	1.86	1.86	1.87	1.91
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*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core™ i5 processor at 1.7 Ghz and 4 Gbyte DDR3 memory at 1.333 Ghz.

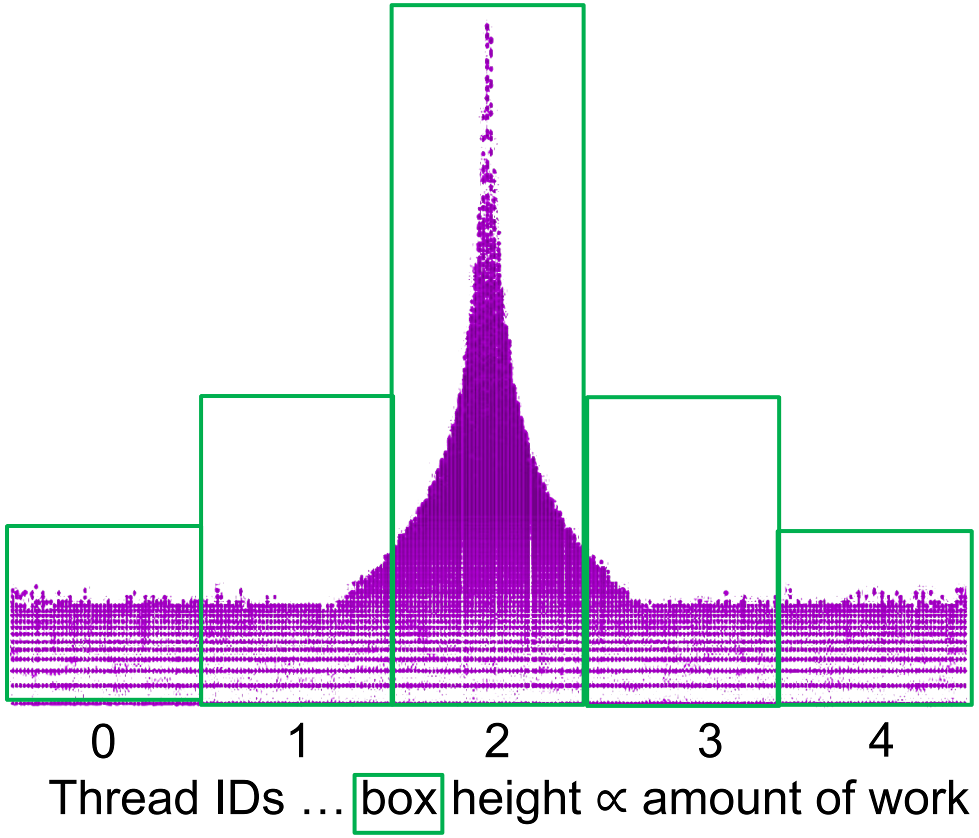
…. Let's pause a moment and consider one of the fundamental issues EVERY parallel programmer must grapple with

Load Balancing

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

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

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



Load Balancing

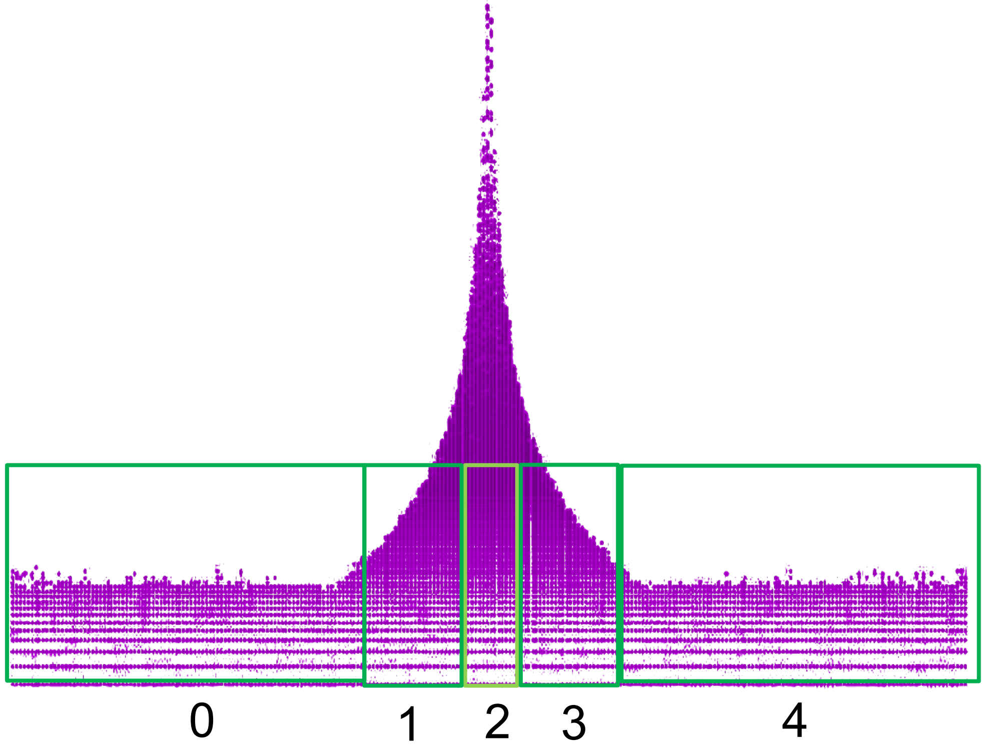
- A parallel job isn’t done until the last thread is finished

- The work in our problem is unevenly distributed spatially.

- A key part of parallel programming is to design how you partition the work between threads so every thread has about the same amount of work.

- This topic is referred to as *Load Balancing*.

- In this case we adjusted the size of each chunk to equalize the work assigned to each thread.
  - Getting the right sized chunks for a variable partitioning (as done here) can be really difficult.

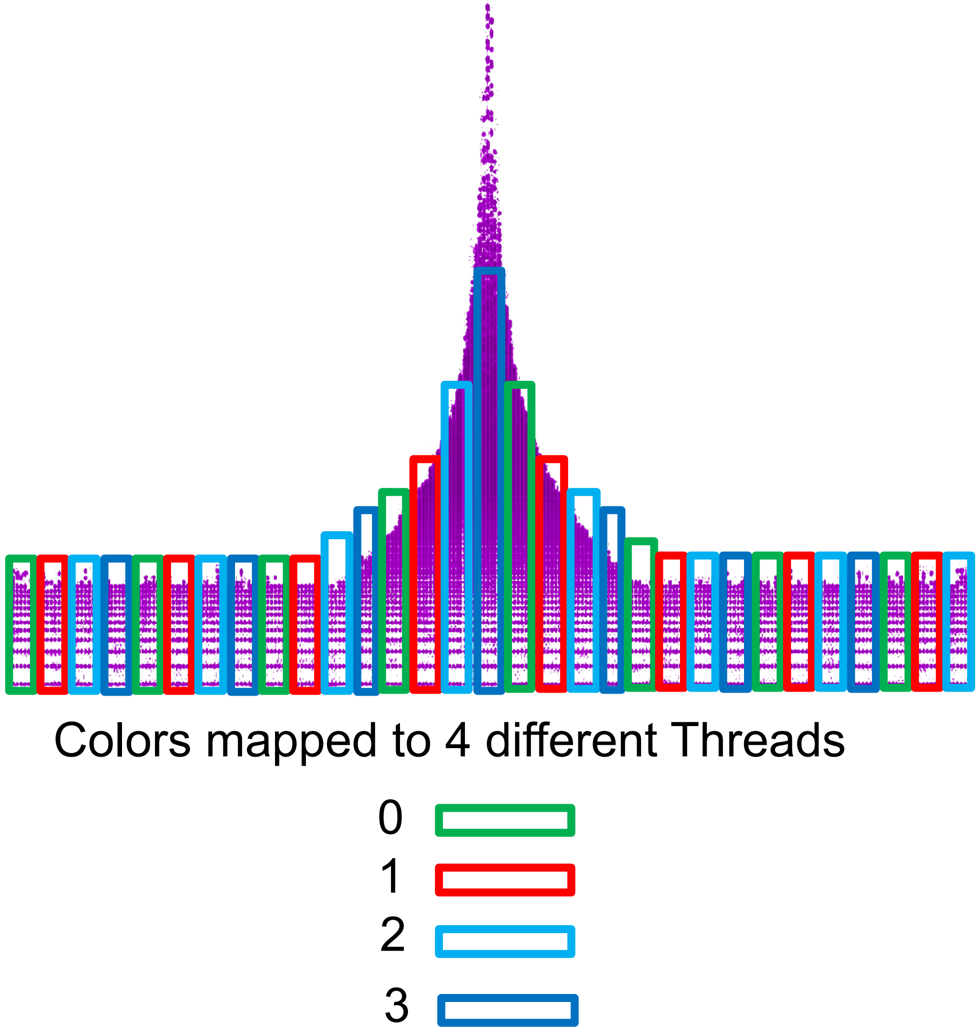


Thread IDs … box height ∝ amount of work

Load Balancing

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

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



Colors mapped to 4 different Threads

Load Balancing

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

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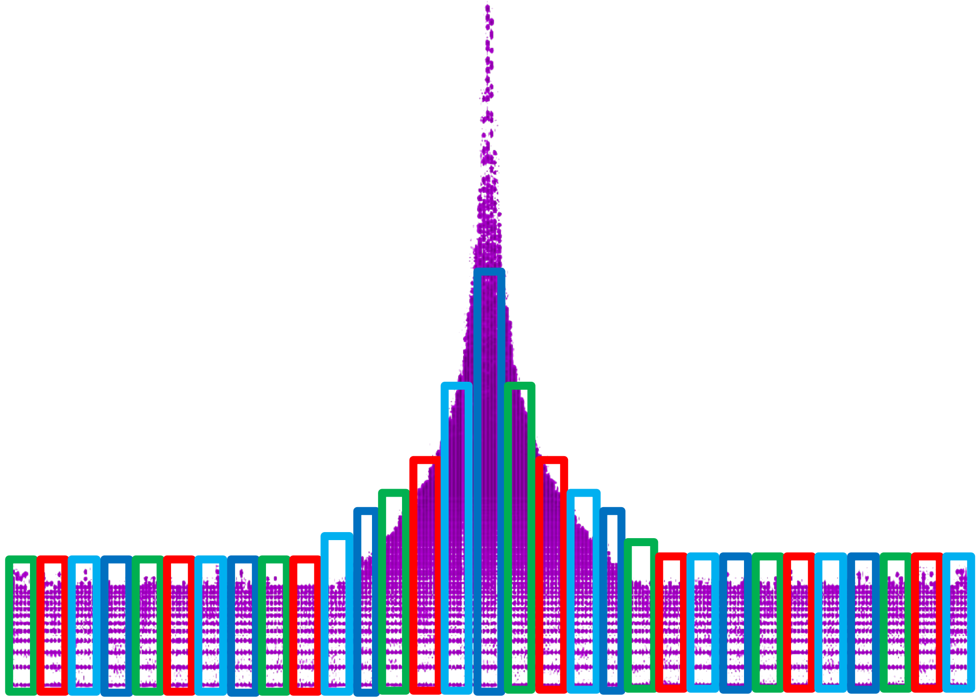
    - Over-decompose the problem into small, fine-grained chunks
    - Spread the chunks out among the threads (in this case using a cyclic distribution)
    - The work is spread out and statistically, you are likely to get a good distribution of work

- 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



Colors mapped to 4 different Threads

0 🟩
1 🟥
2 🟦
3 🟦

Loop Worksharing Constructs: The schedule clause

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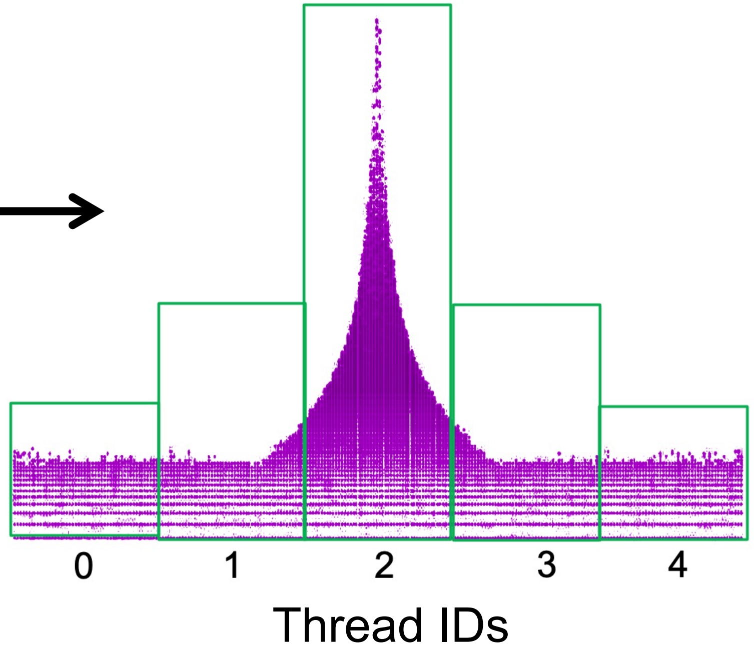
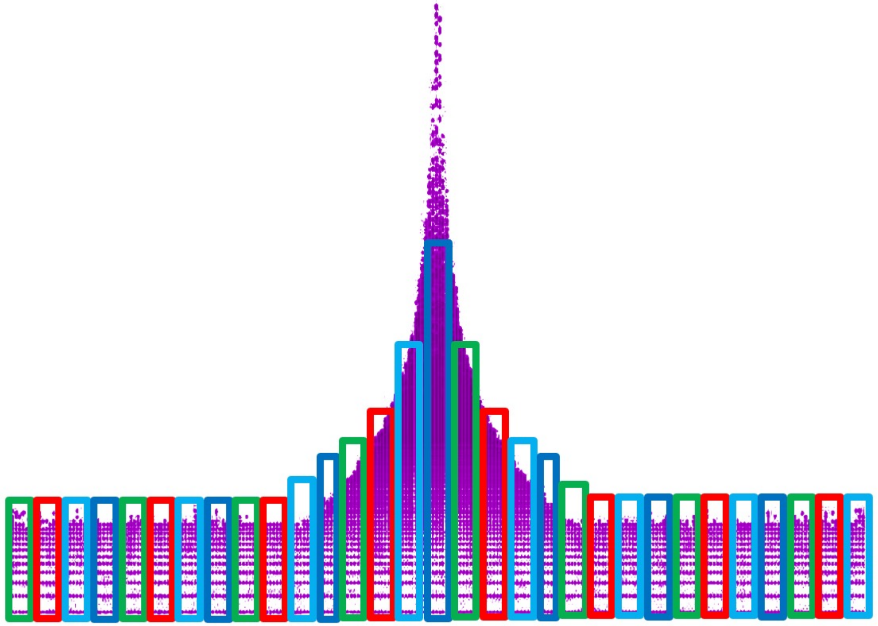
Loop Worksharing Constructs: The schedule clause

- The schedule clause … most common cases:

#pragma omp parallel for schedule (static)





Colors mapped to 4 different Threads

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

no implicit barrier due to nowait

implicit barrier at the end of a parallel region

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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.

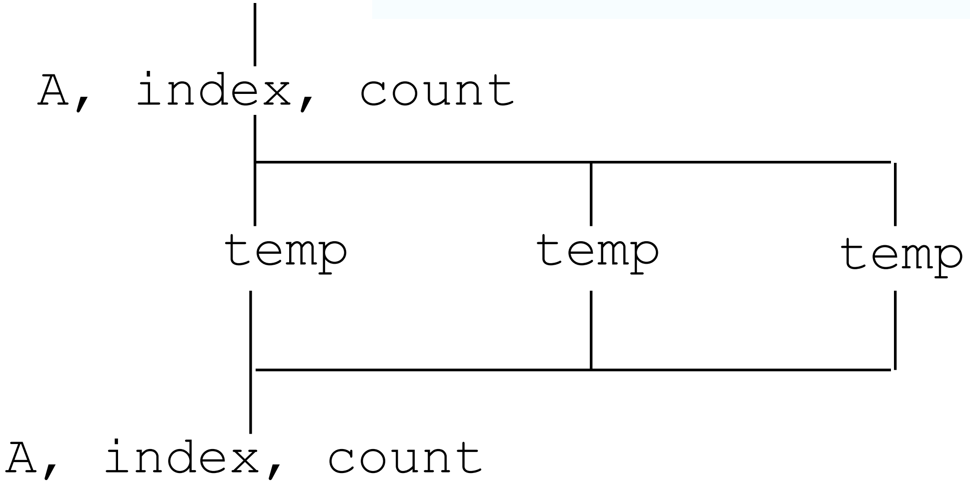
Data Sharing: Examples

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

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

A, index and count are shared by all threads.

temp is local to each thread



Data Sharing: Changing storage attributes

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

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

default() can only be used on parallel constructs

Data Sharing: Private clause

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

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



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


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

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

Data Sharing: Private clause

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

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

tmp was not initialized

tmp is 0 here

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

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

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.

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

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

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.

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

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

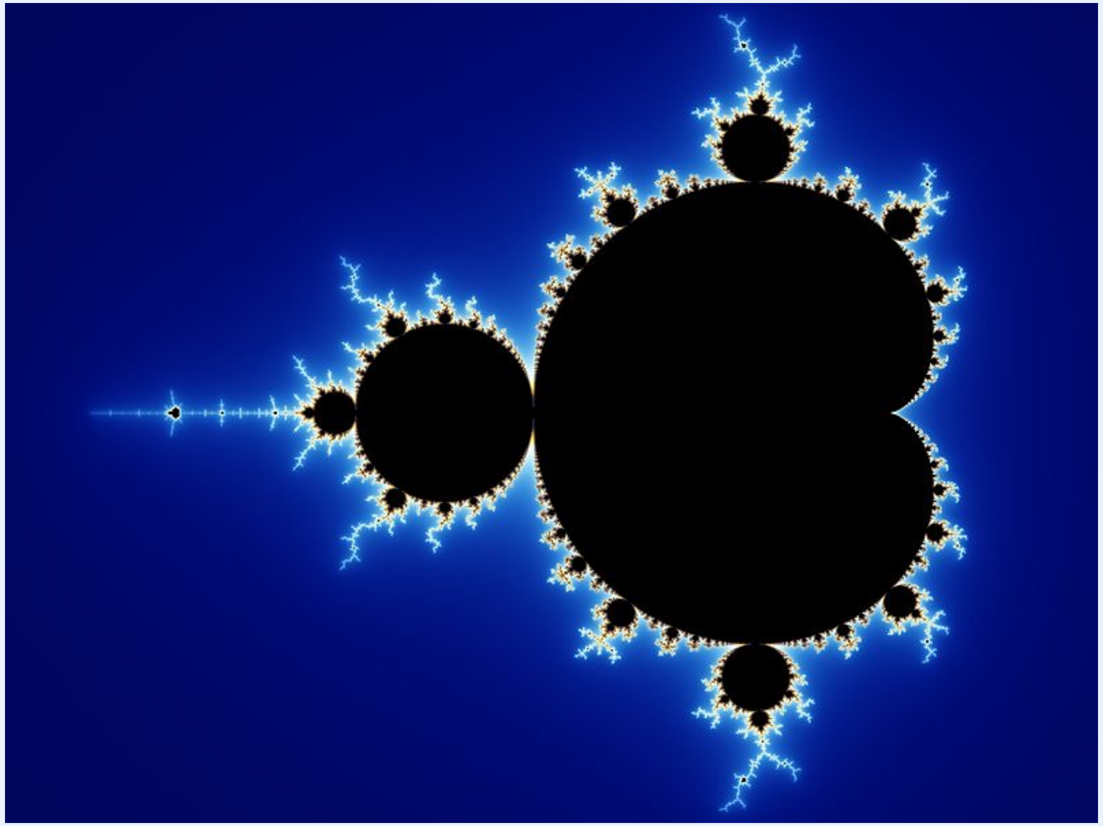


Image Source: Created by Wolfgang Beyer with the program Ultra Fractal 3. - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=321973

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 $z_0 = 0$.

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

The Mandelbrot Set Area Program (original code)

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

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

       zr=C_real;     zi=C_imag;
       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++;
                  break;  // exit the loop
         }
       }
       return 0;
}
```

The Mandelbrot Set Area Program

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

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

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

- eps was not initialized
- Data race on j, C_real, and C_imag
- Protect updates of numoutside

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

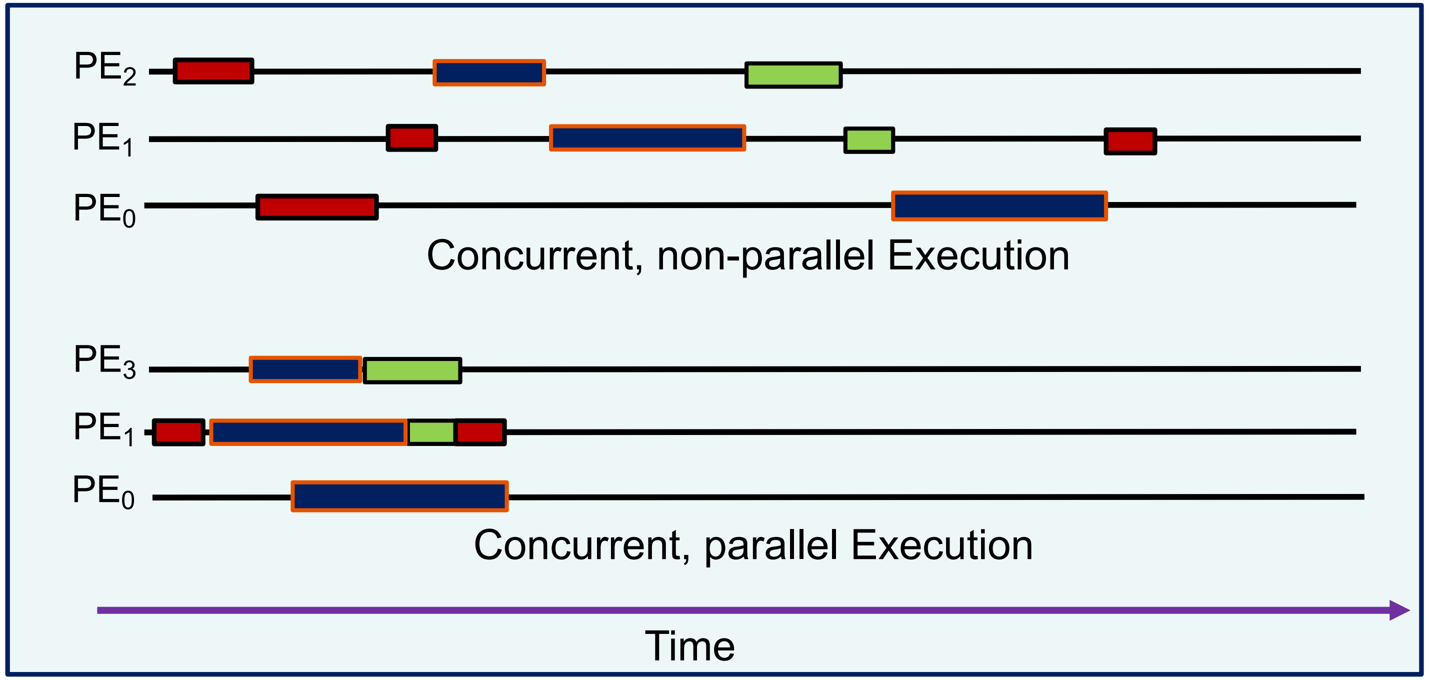
Outline

- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- ➡ Memory Model
- Irregular Parallelism and Tasks
- Worksharing Revisited
- Synchronization Revisited: Options for Mutual exclusion
- Threadprivate and the joys of “random” numbers
- Recap

Concurrency vs. Parallelism

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

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



The fundamental execution model of Multithreading

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

PE = Processing Element

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

Consider two threads: a producer/consumer pair

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

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

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

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

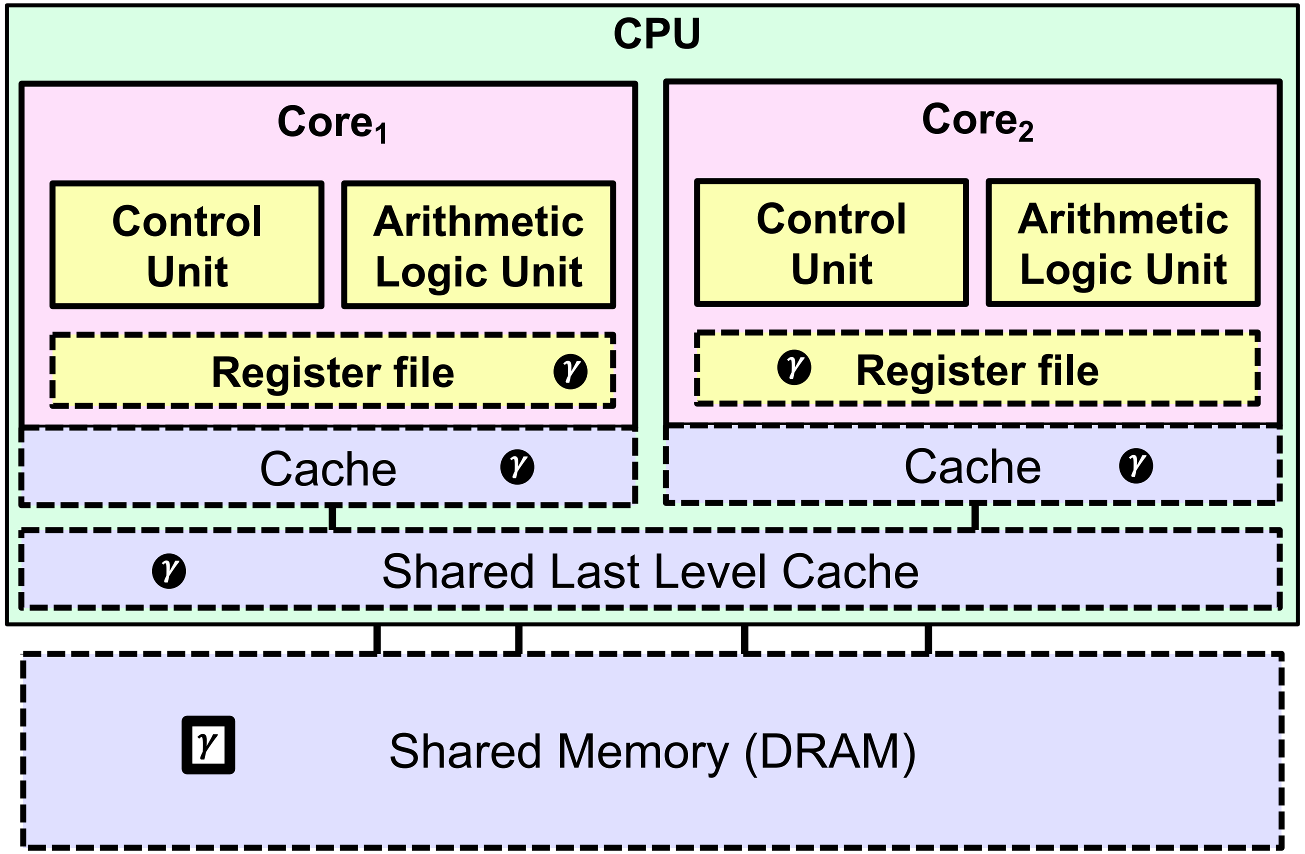
In the jargon of concurrent programming, this is called a "spin lock"

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

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

Memory Models …

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



CPU

Core$_1$

Control Unit

Arithmetic Logic Unit

Register file γ

Cache γ

Core$_2$

Control Unit

Arithmetic Logic Unit

γ **Register file**

Cache γ

γ Shared Last Level Cache

γ Shared Memory (DRAM)

- 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.
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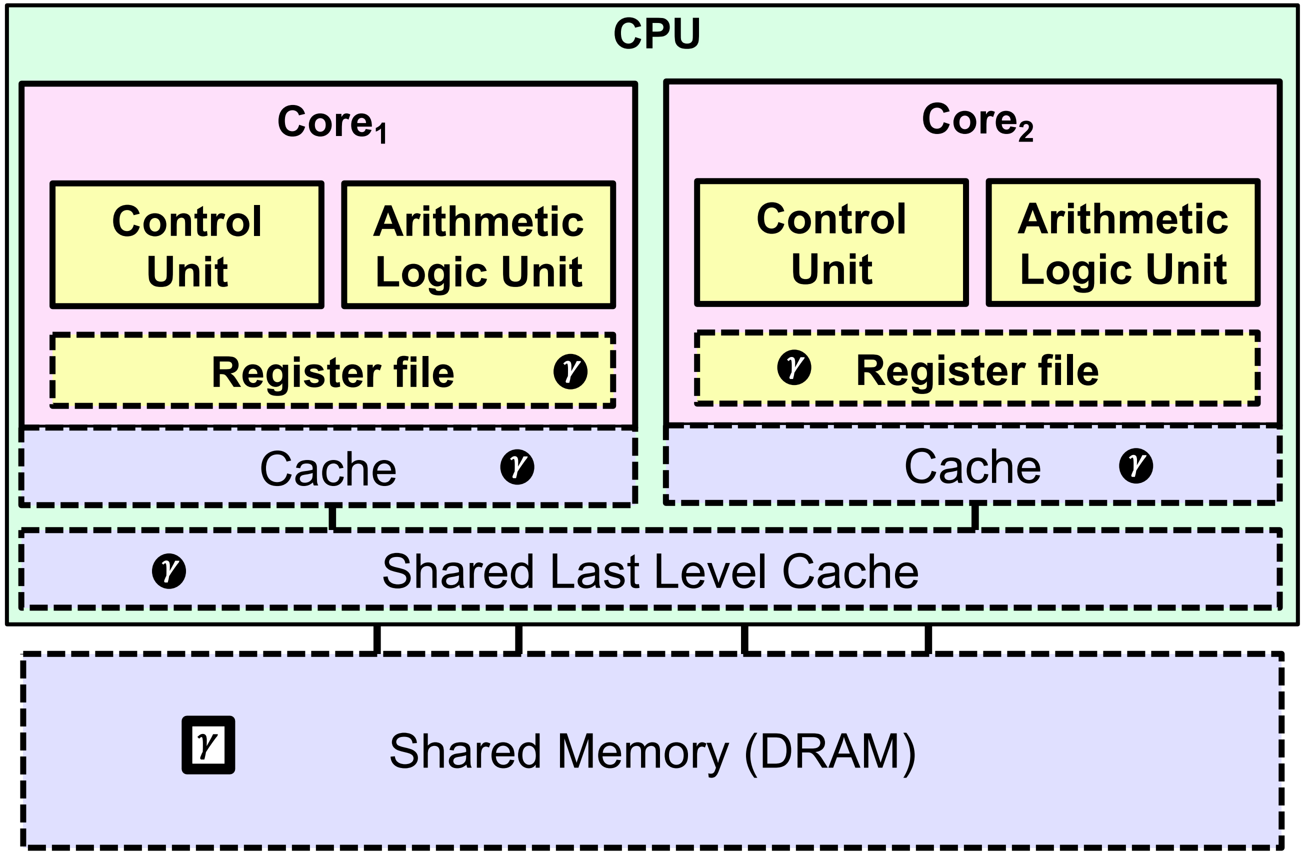


A memory consistency model (or "**memory model**" for short) provides the rules needed to answer this question.

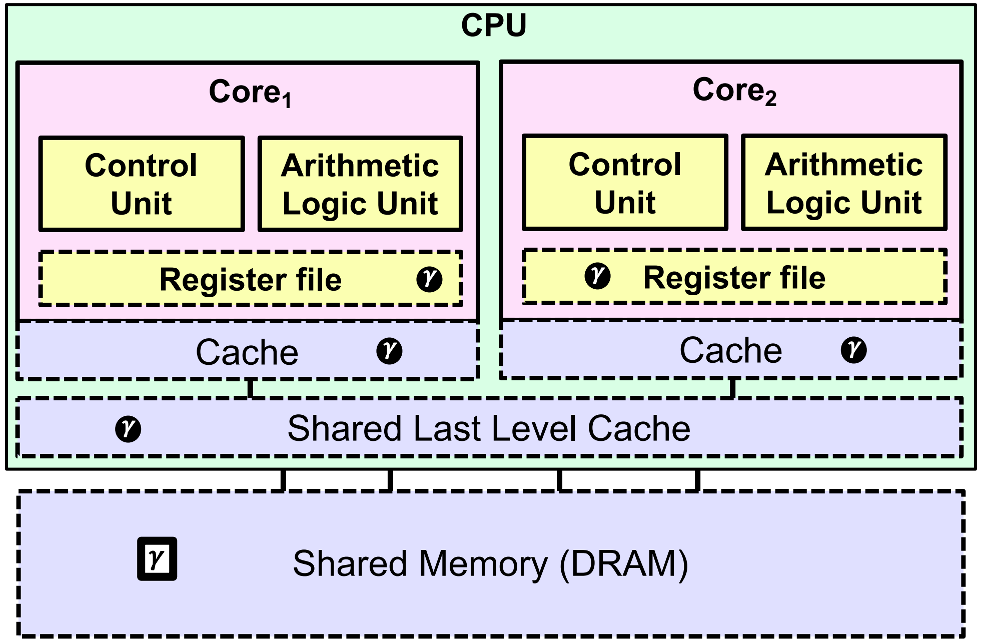
- Which value of γ is the one a thread should see at any point in a computation?

Memory Models …

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

1. **Sequential Consistency**

- Threads execute and the associated loads/stores appear in some order defined by the semantically allowed interleaving of program statements.
- **All threads see the same interleaved order of loads and stores**



2. **Relaxed Consistency**

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

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

Why did this program fail?

Two issues:

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

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

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

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

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

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

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

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

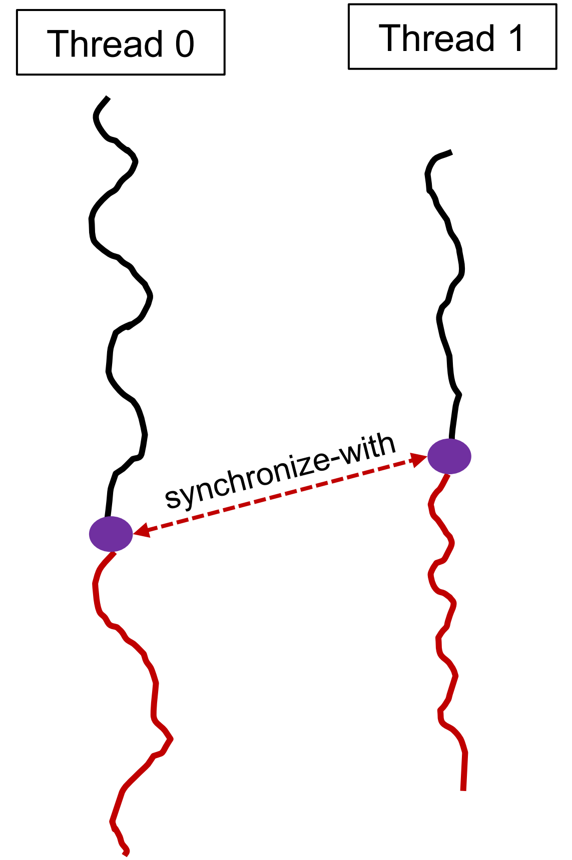
Regardless of how the compiler orders stores to **answer** and **flag**, thread 1 may see a different order than thread 0

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

- Single thread execution:
  - Program order ... Loads and stores appear to occur in the order defined by the program's semantics. If you can't observe it, however, compilers can reorder instructions to maximize performance.

- Multithreaded execution … concurrency in action
  - The compiler doesn't understand instruction-ordering across threads … loads/stores to shared memory across threads can expose ambiguous orders of loads and stores
  - Instructions between threads are unordered except when specific ordering constraints are imposed, i.e., **synchronization**.
  - Synchronization lets us force that some instructions **happens-before** other instructions

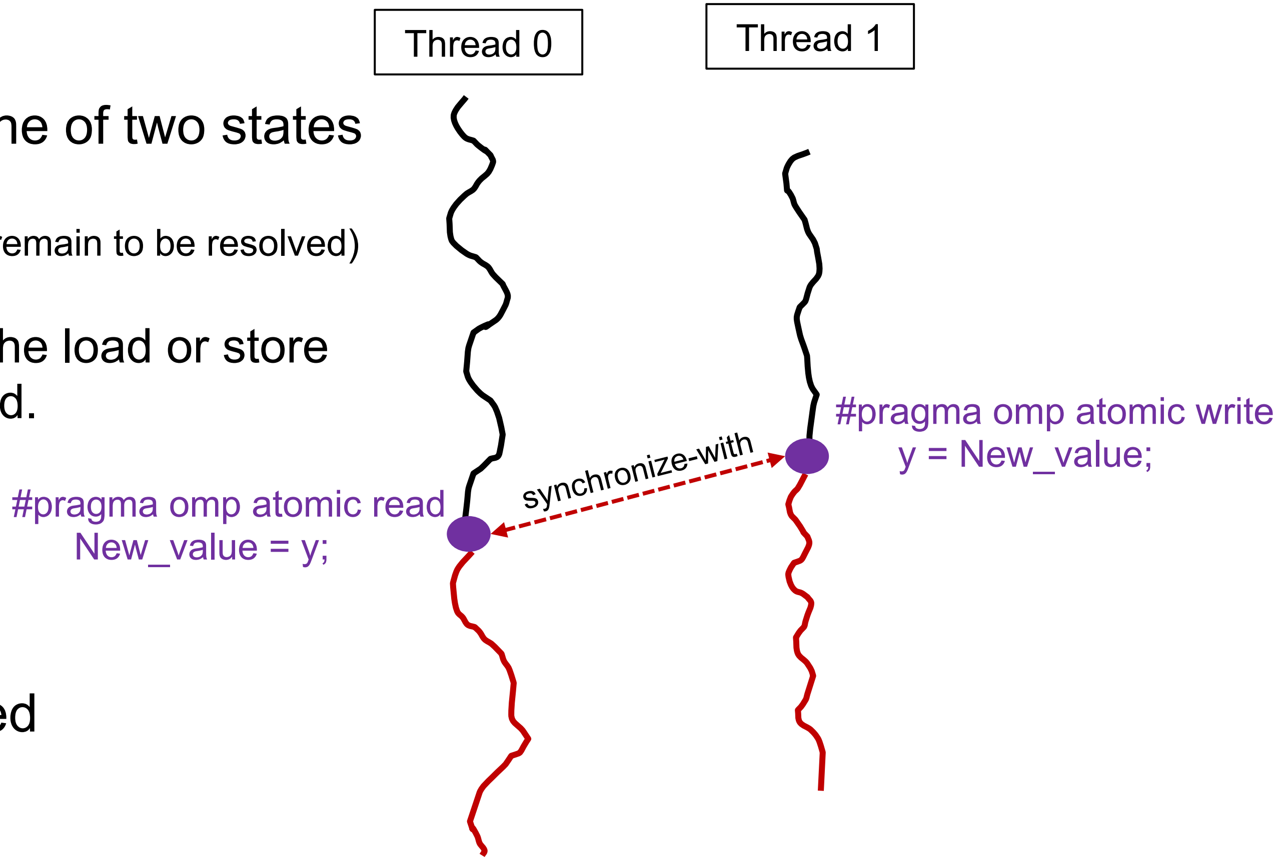
- Two parts to synchronization:
  - A **synchronize-with** relationship exists at statements in 2 or more threads at which memory order constraints can be established.
  - **Memory order**: defines the view of loads/stores on either side of a synchronized-with operations.



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

Atomic Operations and Synchronized-with

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



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

Memory orders

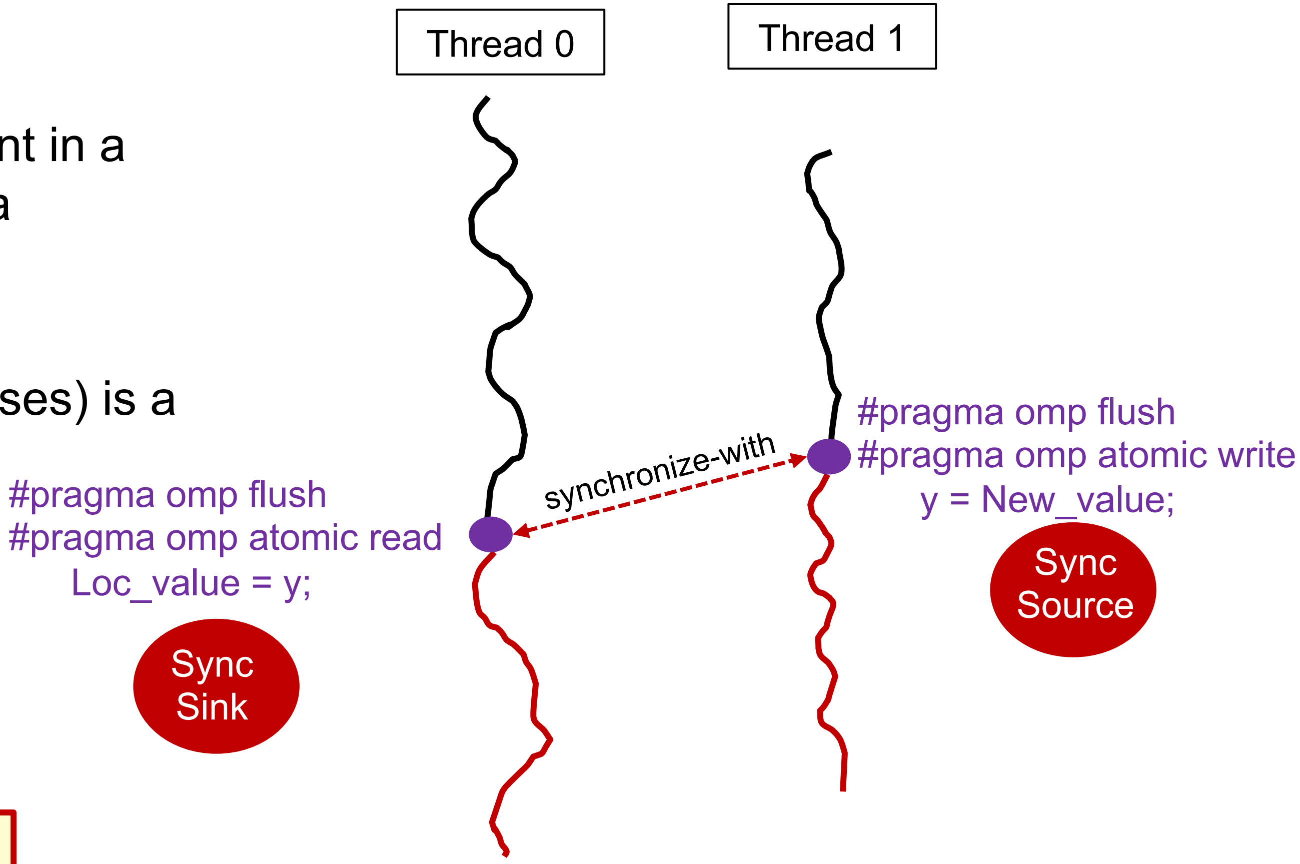
- Memory orders establish which loads and stores can be moved around synchronized-with relations.

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

- The default case for flush (i.e., no additional clauses) is a **strong flush**:
  - Previous read/writes by this thread have completed and are visible to other threads
  - No subsequent read/writes by this thread have occurred

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

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



Thread 0

Thread 1

#pragma omp flush
#pragma omp atomic write
y = New_value;

Sync Source

synchronize-with

#pragma omp flush
#pragma omp atomic read
Loc_value = y;

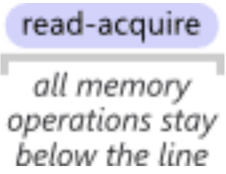
Sync Sink

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.

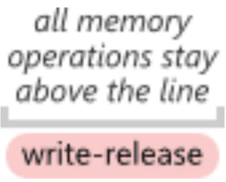
Black operations on Thread 1 happen-before Red operations on thread 0.

Memory orders

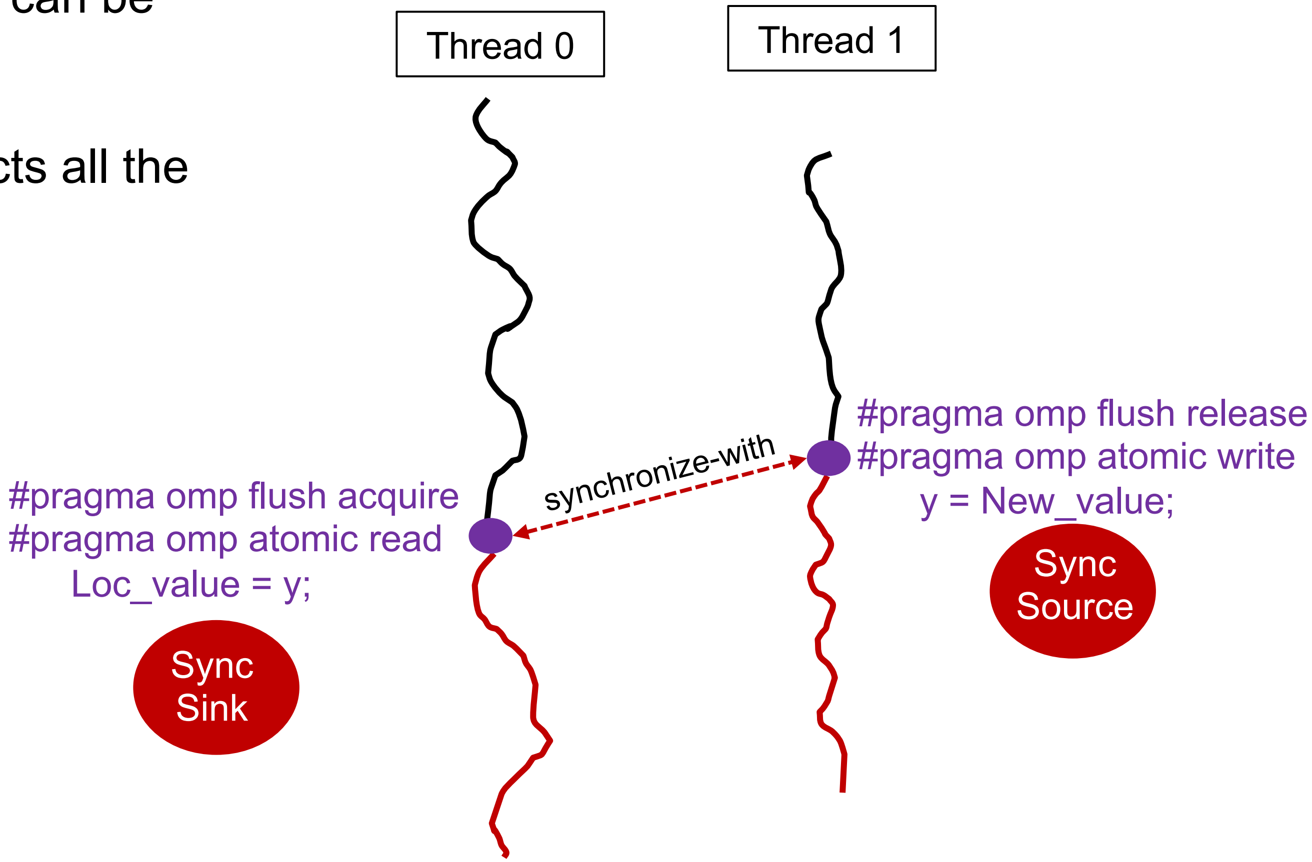
- Memory orders establish which loads and stores can be moved around synchronized-with relations.
- The strong flush by itself is expensive as it impacts all the shared variables visible to a thread.
- There are more focused forms of memory order
  The 2 most fundamental memory orders are:



  - 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 flush acquire
#pragma omp atomic read
    Loc_value = y;
```

```
#pragma omp flush release
#pragma omp atomic write
    y = New_value;
```

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.
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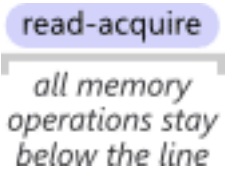

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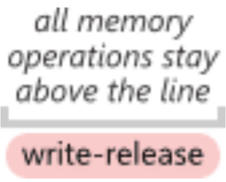
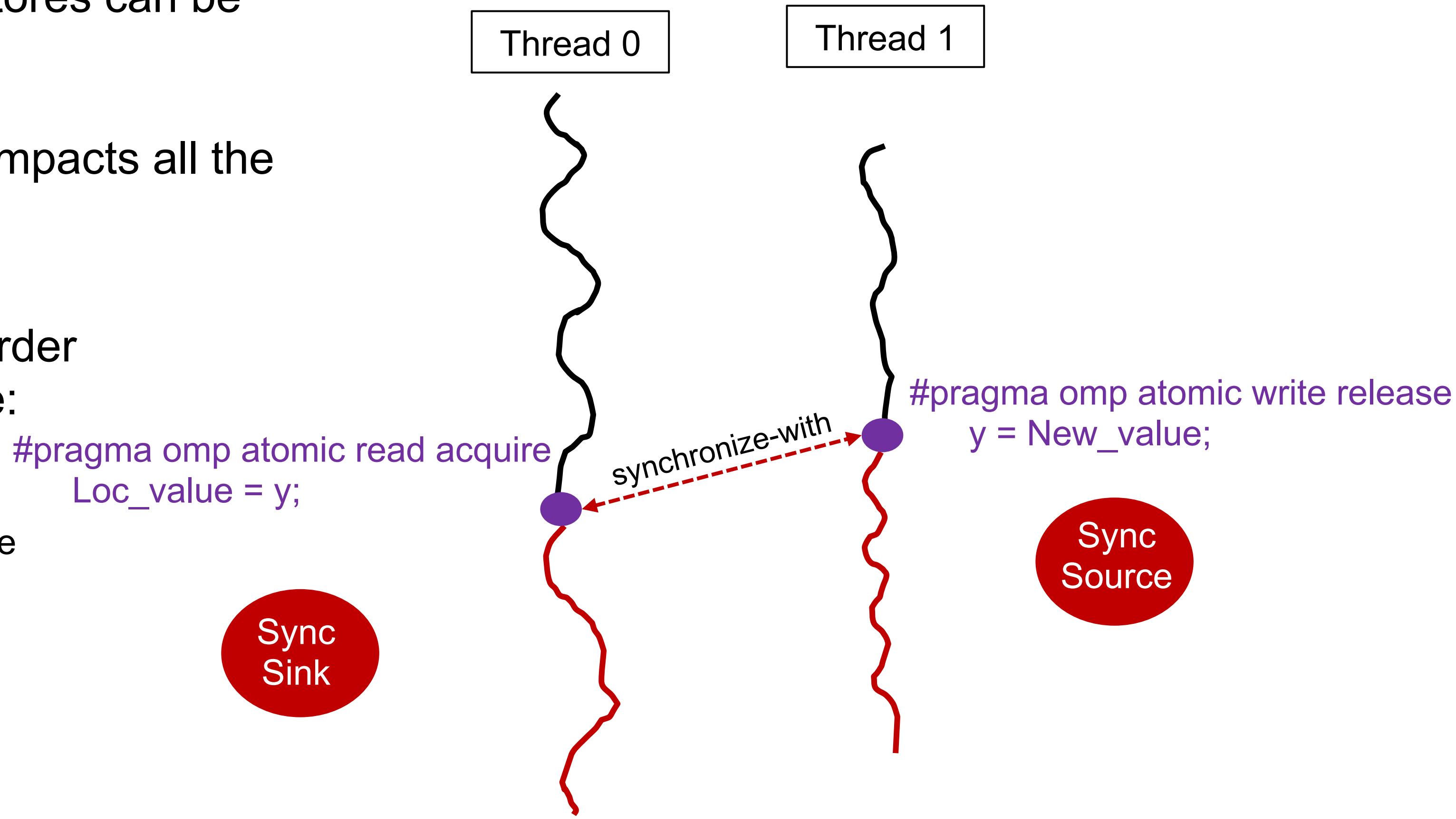


  - Release: Reads/Writes prior to the write-with-release must happen-before the write-with-release.



#pragma omp atomic read acquire
Loc_value = y;

#pragma omp atomic write release
y = New_value;

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

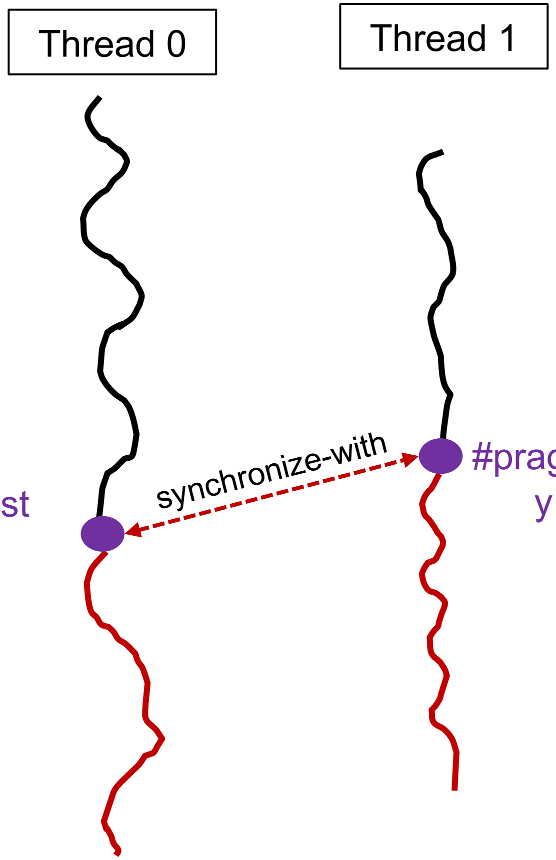
We can combine the flush and the atomic constructs

producer/consumer program correctly synchronized

```
#include <stdio.h>
#include <omp.h>
#define COUNT 1000000
int main()
{
  int answer = 0, flag= 0,err=0;
  #pragma omp parallel shared(flag,answer) num_threads(2)
  {
    int id = omp_get_thread_num();
    if (id == 0) {
       answer = 42;
       #pragma omp 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)



```
#pragma omp atomic read seq_cst
    New_value = y;
```

```
#pragma omp atomic write seq_cs
    y = New_value;
```

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

The most important memory order to use is seq_cst.

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

]

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

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

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

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

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

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

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

Outline

- Introduction to OpenMP
- Creating Threads
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- Parallel Loops
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- ➡ Irregular Parallelism and Tasks
- Worksharing Revisited
- Synchronization Revisited: Options for Mutual exclusion
- Threadprivate and the joys of “random” numbers
- Recap

Irregular Parallelism

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

- Example: Traversing Linked lists:

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

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

Exercise: Traversing linked lists

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

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

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

Linked Lists with OpenMP (without tasks)

- See the file solutions/linked_notasks.c

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

Count number of items in the linked list

Copy pointer to each node into an array

Process nodes in parallel with a for loop

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

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

Linked Lists with OpenMP (without tasks)

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

Count number of items in the linked list

Copy pointer to each node into an array

Process nodes in parallel with a for loop

Number of threads	Schedule	
	Default	Static,1
1	48 seconds	45 seconds
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With so much code to add and three passes through the data, this is really ugly.

There has got to be a better way to do this

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

Solutions from other people

- A much more elegant solution 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 its own copy of the list pointer set to the head of the list

Each thread advances its list pointer by a number equal to the thread ID

Increment the thread’s list pointer by the number of threads

Solutions from other people

- A particularly elegant, SPMD solution

```
#pragma omp parallel firstprivate(p)
  {
     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 its 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 give node using the modulus of the count with the number of threads

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;
      }
  }
```

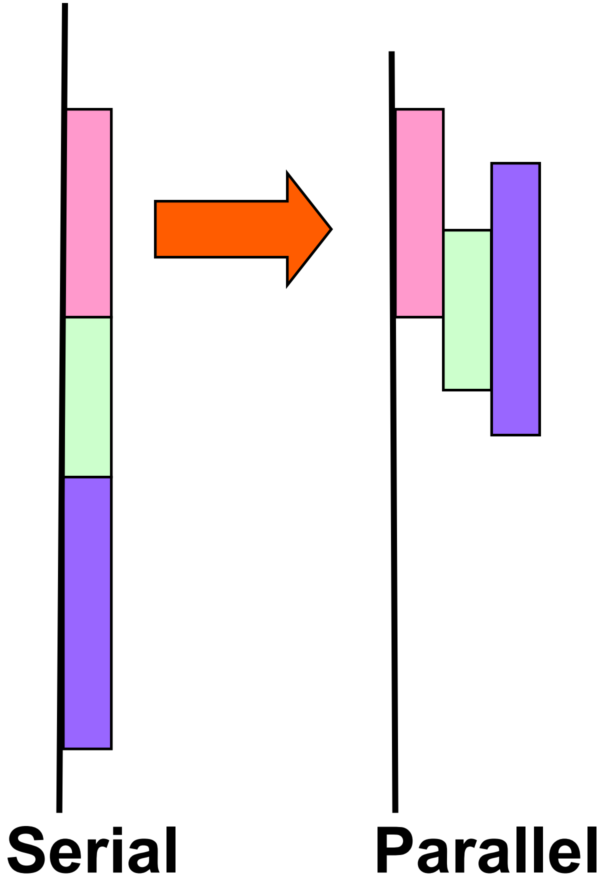
```
#pragma omp parallel firstprivate(p)
  {
     int id = omp_get_thread_num();
     int nthreads = omp_get_num_threads();
     int count = 0;
     while(p!=NULL && count < id){
        count ++;
        p = p->next;
     }
     while (p != NULL) {
        processwork(p);
        int count = 0;
   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

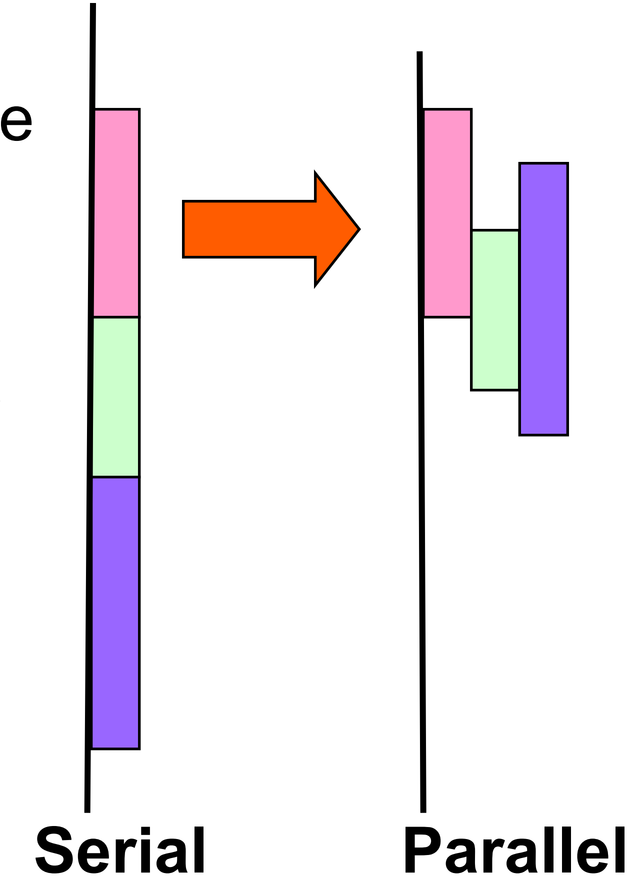
What are Tasks?

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

Create some threads

One Thread packages tasks

Tasks executed by some thread in some order

All tasks complete before this barrier is released

Exercise: Simple tasks

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

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

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

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

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

This exercise comes from Ruud van der Pas of Oracle

Racey Cars: Solution

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

Data Scoping with Tasks

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

- These concepts are a little bit different compared with threads:
  - If a variable is shared on a task construct, the references to it inside the construct are to the storage with that name at the point where the task was encountered

  - If a variable is private on a task construct, the references to it inside the construct are to new uninitialized storage that is created when the task is executed

  - If a variable is firstprivate on a construct, the references to it inside the construct are to new storage that is created and initialized with the value of the existing storage of that name when the task is encountered

Data Scoping Defaults

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

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

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

A is shared
B is firstprivate
C is private

Exercise: Traversing linked lists

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

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

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

Parallel Linked List Traversal

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

Only one thread packages tasks

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

When/Where are Tasks Complete?

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

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

    `#pragma omp taskwait`
  - Note: applies only to tasks generated in the current task, not to “descendants” .

Example

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

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

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

Example

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

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

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

Example: Fibonacci numbers

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

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

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

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

Parallel Fibonacci

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

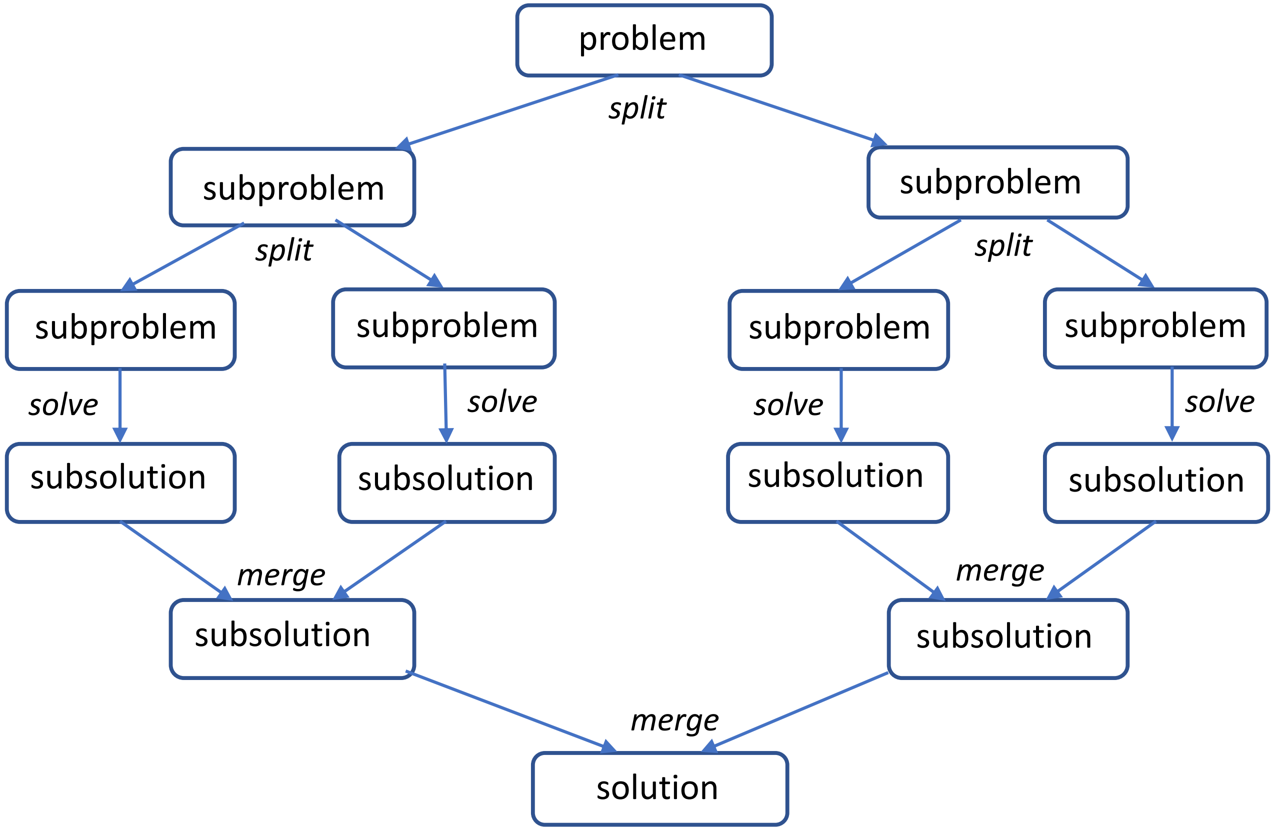
#pragma omp task shared(x)
   x = fib(n-1);
#pragma omp task shared(y)
   y = fib (n-2);
#pragma omp taskwait
   return (x+y);
}

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

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

Divide and Conquer

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



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

Exercise: PI with tasks

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

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

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

Program: OpenMP tasks

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

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

Results*: Pi with tasks

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

*Intel compiler (icpc) with no optimization on Apple OS X 10.7.3 with a dual core (four HW thread) Intel® Core^{TM} 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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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);
        }
}
```

Loop construct name:

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

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

Loop Worksharing Constructs: The schedule clause

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

OpenMP 4.5 added modifiers monotonic, nonmontonic and simd.

Loop Worksharing Constructs: The schedule clause

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

Least work at runtime : scheduling done at compile-time

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

Nested Loops

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

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

Number of loops to be parallelized, counting from the outside

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

Sections Worksharing Construct

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

```
#pragma omp parallel
{

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

}
```

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

Array Sections with Reduce

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

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

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

Exercise

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

Optimizing mandel.c

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

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

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

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

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

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

Synchronization: Lock Routines

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

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

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

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

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

Synchronization: Simple Locks Example

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

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

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

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

One lock per case … even and odd

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

Free-up storage when done.

Exercise

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

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

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

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

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

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

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

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

      hist[ival]++;

   }

  time = omp_get_wtime() - time;

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

Only focus on this part of the program

Histogram Program: Critical section

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

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

Easy to write and correct, but terrible performance

Histogram program: one lock per histogram bin

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

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

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

One lock per element of hist

Enforce mutual exclusion on update to hist array

Free-up storage when done.

Histogram program: reduction with an array

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

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

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

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

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

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Data Sharing: Threadprivate

- Makes global data private to a thread
  - Fortran: **COMMON** blocks
  - C: File scope and static variables, static class members

- Different from making them **PRIVATE**
  - with **PRIVATE** global variables are masked.
  - THREADPRIVATE preserves global scope within each thread

- Threadprivate variables can be initialized using **COPYIN** or at time of definition (using language-defined initialization capabilities)

A Threadprivate Example (C)

Use threadprivate to create a counter for each thread.

```
int counter = 0;
#pragma omp threadprivate(counter)

int increment_counter()
{
    counter++;
    return (counter);
}
```

Data Copying: Copyin

You initialize threadprivate data using a copyin clause.

```
      parameter (N=1000)
      common/buf/A(N)
!$OMP THREADPRIVATE(/buf/)

!$ Initialize the A array
      call init_data(N,A)

!$OMP PARALLEL COPYIN(A)

 … Now each thread sees threadprivate array A initialized
 … to the global value set in the subroutine init_data()

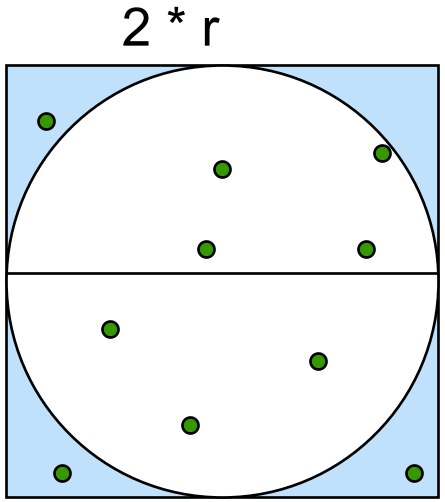
!$OMP END PARALLEL

end
```

Exercise: Monte Carlo Calculations

Using random numbers to solve tough problems

- Sample a problem domain to estimate areas, compute probabilities, find optimal values, etc.
- Example: Computing π with a digital dart board:



N= 10	π = 2.8
N=100	π = 3.16
N= 1000	π = 3.148

- Throw darts at the circle/square.
- Chance of falling in circle is proportional to ratio of areas:

  $A_c = r^2 * \pi$

  $A_s = (2*r) * (2*r) = 4 * r^2$

  $P = A_c/A_s = \pi /4$
- Compute π by randomly choosing points; π is four times the fraction that falls in the circle

Exercise: Monte Carlo pi (cont)

- We provide three files for this exercise
  - pi_mc.c: the Monte Carlo method pi program
  - random.c: a simple random number generator
  - random.h: include file for random number generator
- Create a parallel version of this program.
- Run it multiple times with varying numbers of threads.
- Is the program working correctly? Is there anything wrong?

Parallel Programmers love Monte Carlo algorithms

```
#include "omp.h"
static long num_trials = 10000;
int main ()
{
   long i;      long Ncirc = 0;       double pi, x, y;
   double r = 1.0;   // radius of circle. Side of squrare is 2*r
   seed(0,-r, r);  // The circle and square are centered at the origin
   #pragma omp parallel for private (x, y) reduction (+:Ncirc)
   for(i=0;i<num_trials; i++)
   {
      x = random();         y = random();
      if ( x*x + y*y) <= r*r)   Ncirc++;
    }

    pi = 4.0 * ((double)Ncirc/(double)num_trials);
    printf("\n %d trials, pi is %f \n",num_trials, pi);
}
```

Embarrassingly parallel: the parallelism is so easy its embarrassing.

Add two lines and you have a parallel program.

Random Numbers: Linear Congruential Generator (LCG)

- LCG: Easy to write, cheap to compute, portable, OK quality

```
random_next = (MULTIPLIER  * random_last + ADDEND)% PMOD;
random_last = random_next;
```

- If you pick the multiplier and addend correctly, LCG has a period of PMOD.
- Picking good LCG parameters is complicated, so look it up (Numerical Recipes is a good source). I used the following:
  - MULTIPLIER = 1366
  - ADDEND = 150889
  - PMOD = 714025

LCG code

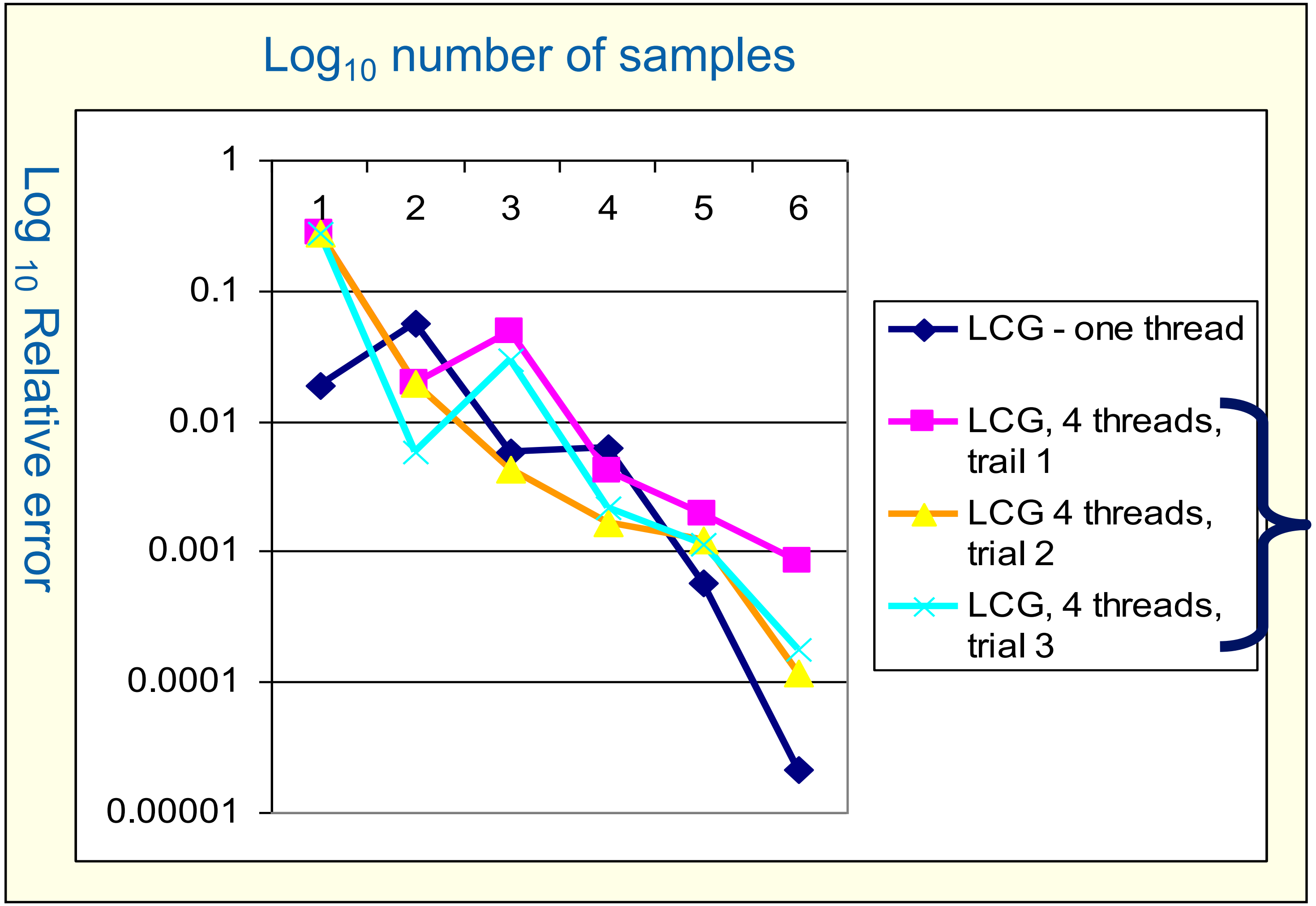
```
static long MULTIPLIER  = 1366;
static long ADDEND      = 150889;
static long PMOD        = 714025;
long random_last = 0;
double random ()
{
    long random_next;

    random_next = (MULTIPLIER  * random_last + ADDEND)% PMOD;
    random_last = random_next;

   return  ((double)random_next/(double)PMOD);
}
```

Seed the pseudo random sequence by setting random_last

Running the PI_MC program with LCG generator



Run the same program the same way and get different answers!

That is not acceptable!

Issue: my LCG generator is not threadsafe

Program written using the Intel C/C++ compiler (10.0.659.2005) in Microsoft Visual studio 2005 (8.0.50727.42) and running on a dual-core laptop (Intel T2400 @ 1.83 Ghz with 2 GB RAM) running Microsoft Windows XP.

Exercise: Monte Carlo pi (cont)

- Create a threadsafe version of the monte carlo pi program

- Do not change the interfaces to functions in random.c
  - This is an exercise in modular software … why should a user of your parallel random number generator have to know any details of the generator or make any changes to how the generator is called?
  - The random number generator must be thread-safe

- Verify that the program is thread safe by running multiple times for a fixed number of threads.

- Any concerns with the program behavior?

LCG code: threadsafe version

```
static long MULTIPLIER  = 1366;
static long ADDEND      = 150889;
static long PMOD        = 714025;
long random_last = 0;
#pragma omp threadprivate(random_last)
double random ()
{
    long random_next;

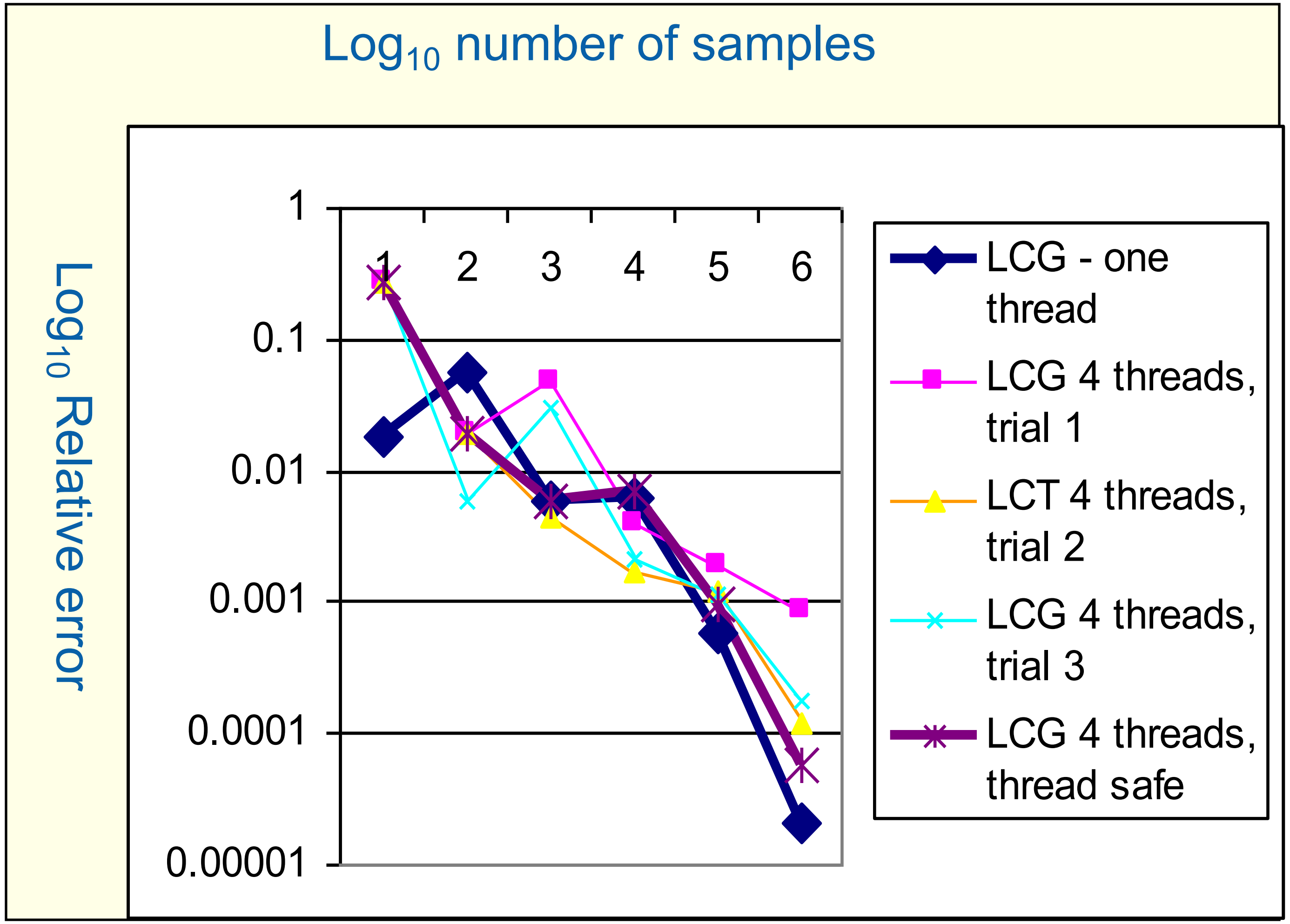
    random_next = (MULTIPLIER  * random_last + ADDEND)% PMOD;
    random_last = random_next;

   return  ((double)random_next/(double)PMOD);
}
```

random_last carries state between random number computations,

To make the generator threadsafe, make random_last threadprivate so each thread has its own copy.

Thread Safe Random Number Generators



Thread safe version gives the same answer each time you run the program.

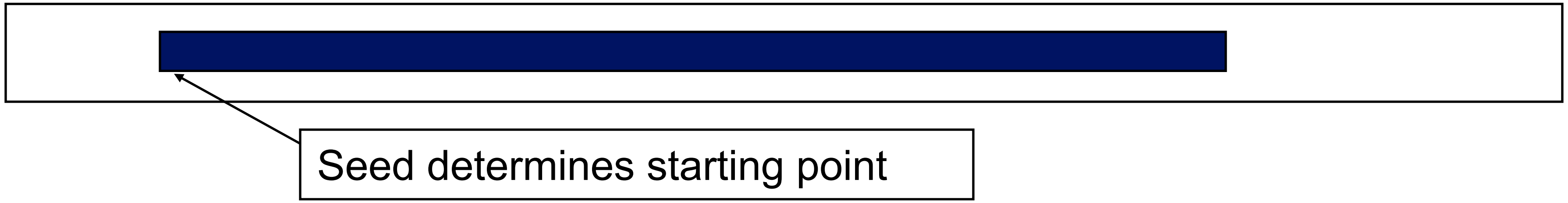
But for large number of samples, its quality is lower than the one thread result!

Why?

Pseudo Random Sequences

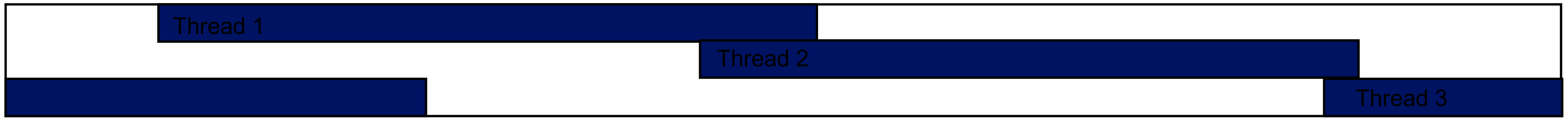
- Random number Generators (RNGs) define a sequence of pseudo-random numbers of length equal to the period of the RNG

- In a typical problem, you grab a subsequence of the RNG range



Seed determines starting point

- Grab arbitrary seeds and you may generate overlapping sequences
  - E.g. three sequences … last one wraps at the end of the RNG period.



- Overlapping sequences = over-sampling and bad statistics … lower quality or even wrong answers!

Parallel random number generators

- Multiple threads cooperate to generate and use random numbers.
- Solutions:
  - Replicate and Pray
  - Give each thread a separate, independent generator
  - Have one thread generate all the numbers.
  - Leapfrog … deal out sequence values “round robin” as if dealing a deck of cards.
  - Block method … pick your seed so each threads gets a distinct contiguous block.

- Other than “replicate and pray”, these are difficult to implement. Be smart … get a math library that does it right.

If done right, can generate the same sequence regardless of the number of threads …

Nice for debugging, but not really needed scientifically.

Intel’s Math kernel Library supports a wide range of parallel random number generators.

For an open alternative, the state of the art is the Scalable Parallel Random Number Generators Library (SPRNG): http://www.sprng.org/ from Michael Mascagni’s group at Florida State University.

MKL Random Number Generators (RNG)

- MKL includes several families of RNGs in its vector statistics library.
- Specialized to efficiently generate vectors of random numbers

```
#define BLOCK 100
double  buff[BLOCK];
VSLStreamStatePtr stream;

vslNewStream(&ran_stream, VSL_BRNG_WH, (int)seed_val);

vdRngUniform (VSL_METHOD_DUNIFORM_STD, stream,
                        BLOCK, buff, low, hi)

vslDeleteStream( &stream );
```

Initialize a stream or pseudo random numbers

Select type of RNG and set seed

Fill buff with BLOCK pseudo rand. nums, uniformly distributed with values between lo and hi.

Delete the stream when you are done

Wichmann-Hill Generators (WH)

- WH is a family of 273 parameter sets each defining a non-overlapping and independent RNG.
- Easy to use, just make each stream threadprivate and initiate RNG stream so each thread gets a unique WG RNG.

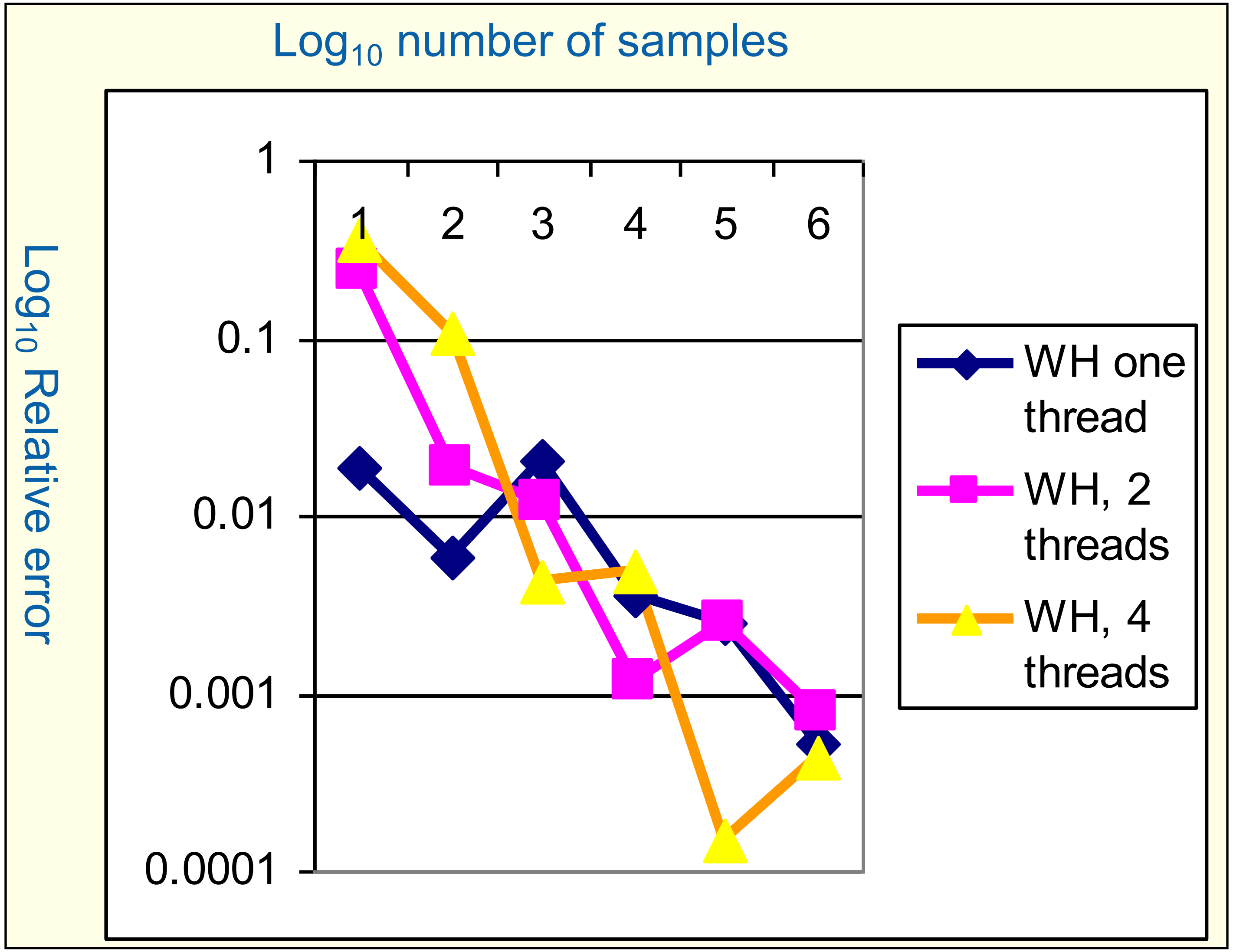
```
VSLStreamStatePtr stream;

#pragma omp threadprivate(stream)

                              …

vslNewStream(&ran_stream, VSL_BRNG_WH+Thrd_ID, (int)seed);
```

Independent Generator for each thread



Notice that once you get beyond the high error, small sample count range, adding threads doesn’t decrease quality of random sampling.

Leap Frog Method

- Interleave samples in the sequence of pseudo random numbers:
  - Thread i starts at the i^th number in the sequence
  - Stride through sequence, stride length = number of threads.
- Result … the same sequence of values regardless of the number of threads.

```
#pragma omp single
{   nthreads = omp_get_num_threads();
     iseed = PMOD/MULTIPLIER;     // just pick a seed
     pseed[0] = iseed;
     mult_n = MULTIPLIER;
     for (i = 1; i < nthreads; ++i)
    {
        iseed = (unsigned long long)((MULTIPLIER * iseed) % PMOD);
        pseed[i] = iseed;
        mult_n = (mult_n * MULTIPLIER) % PMOD;
    }

 }
 random_last = (unsigned long long) pseed[id];
```

One thread computes offsets and strided multiplier

LCG with Addend = 0 just to keep things simple

Each thread stores offset starting point into its threadprivate “last random” value

Same sequence with many threads.

- We can use the leapfrog method to generate the same answer for any number of threads

Steps	One thread	2 threads	4 threads
1000	3.156	3.156	3.156
10000	3.1168	3.1168	3.1168
100000	3.13964	3.13964	3.13964
1000000	3.140348	3.140348	3.140348
10000000	3.141658	3.141658	3.141658

Used the MKL library with two generator streams per computation: one for the x values (WH) and one for the y values (WH+1). Also used the leapfrog method to deal out iterations among threads.

Outline

- Introduction to OpenMP
- Creating Threads
- Synchronization
- Parallel Loops
- Data Environment
- Memory Model
- Irregular Parallelism and Tasks
- Worksharing Revisited
- Synchronization Revisited: Options for Mutual exclusion
- Threadprivate and the joys of “random” numbers
- ➡ Recap

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.

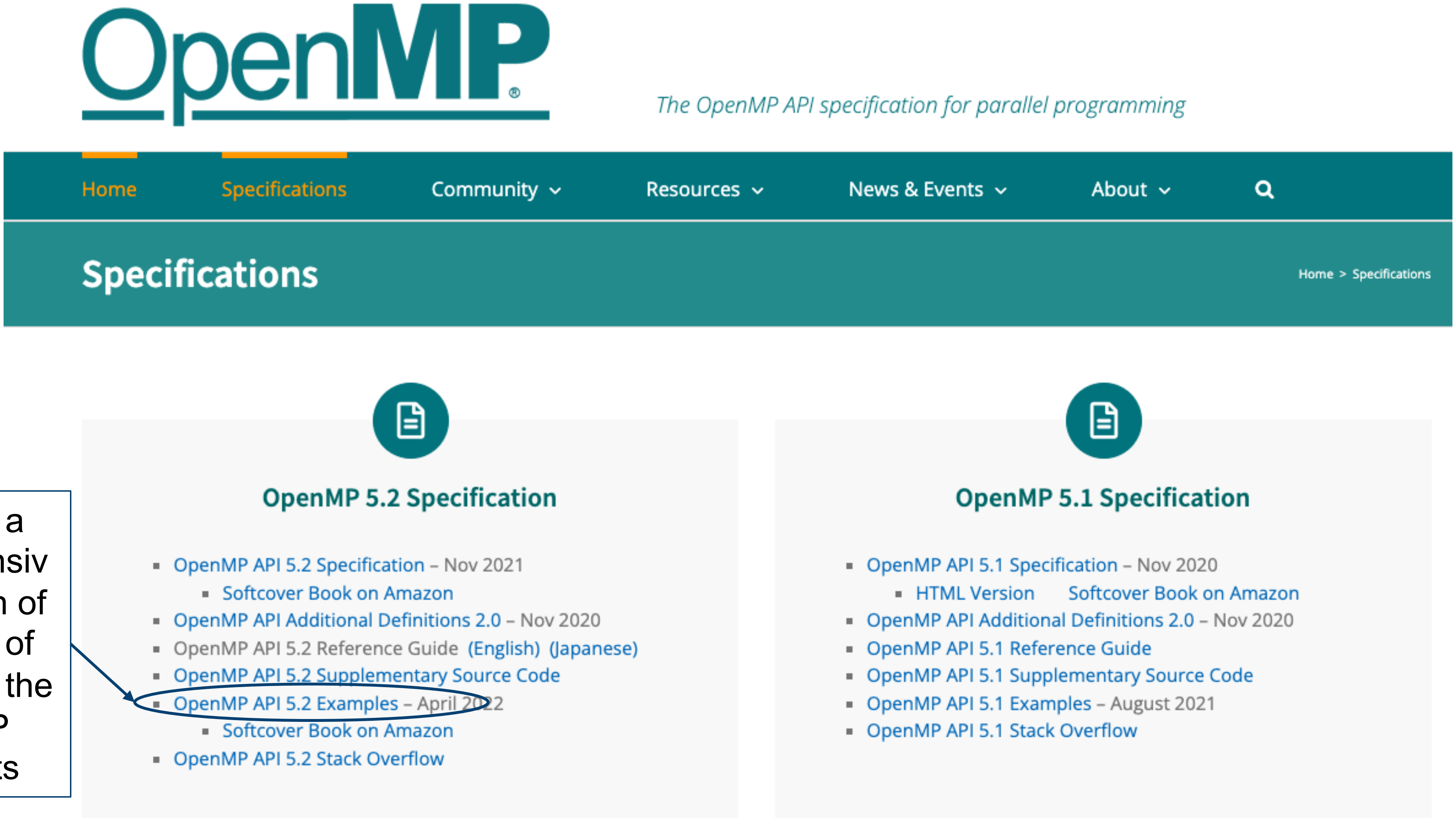
There is Much More to OpenMP than the Common Core

- 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.

Resources

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



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

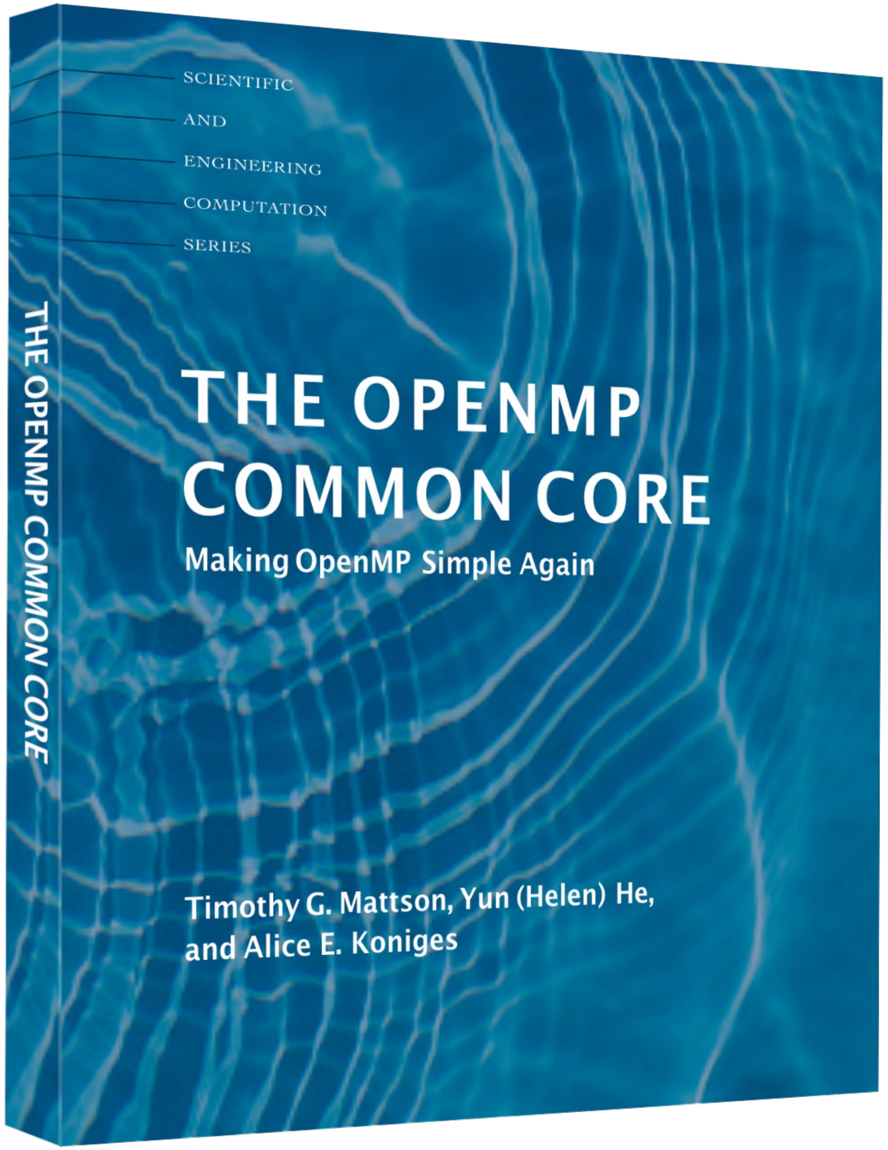
Including a comprehensive collection of examples of code using the OpenMP constructs

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

Books about OpenMP

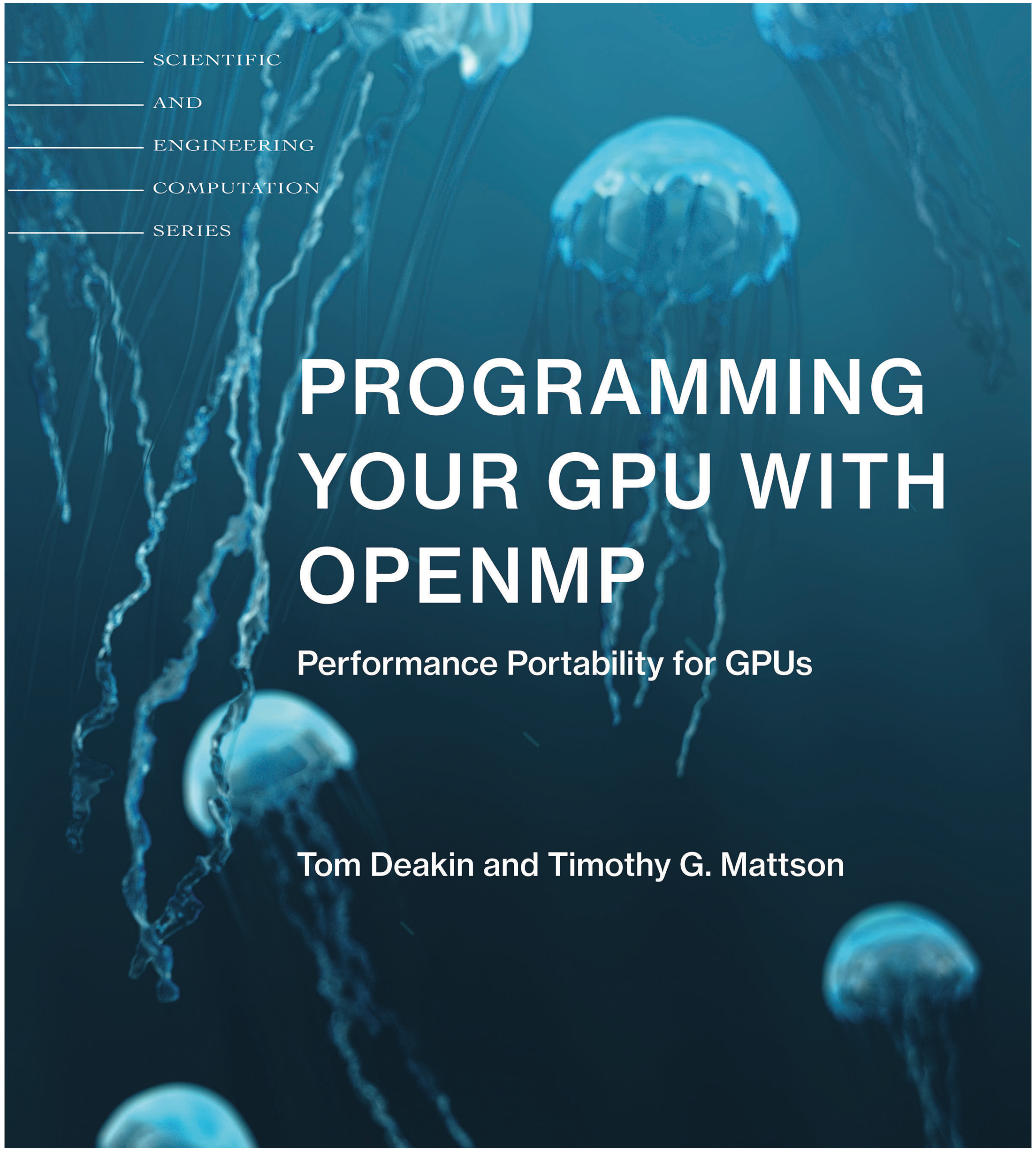
A great book that covers OpenMP features beyond OpenMP 2.5

Books about OpenMP

The latest book on OpenMP …

Came out in early November 2023.

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



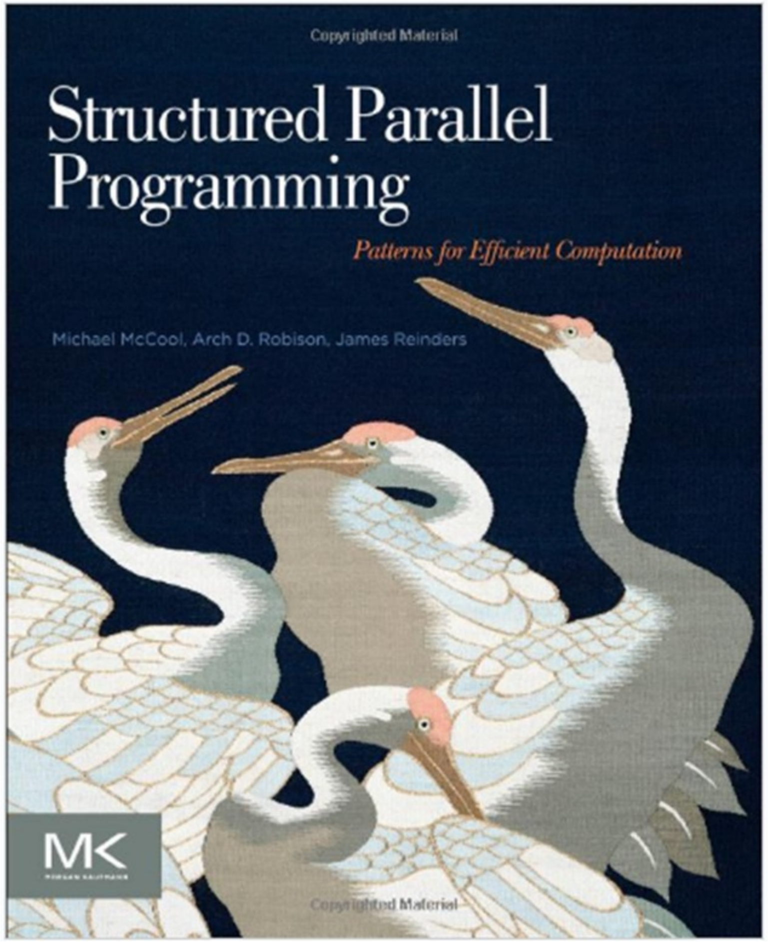
SCIENTIFIC
AND
ENGINEERING
COMPUTATION
SERIES

PROGRAMMING YOUR GPU WITH OPENMP

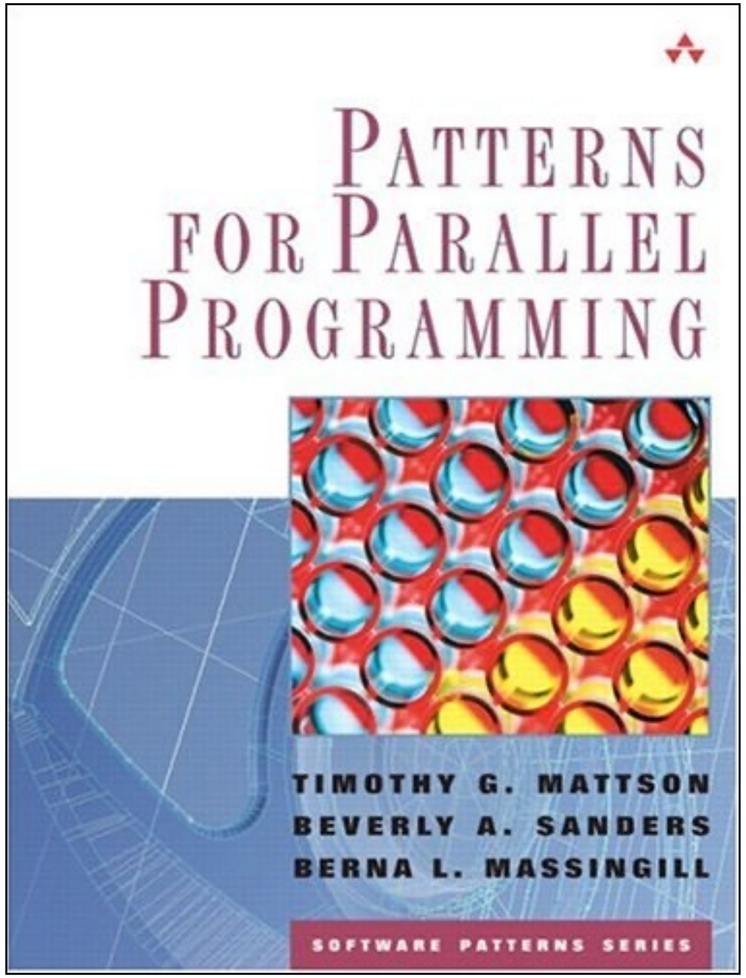
Performance Portability for GPUs

Tom Deakin and Timothy G. Mattson

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