Parallel Programming using OpenMP

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Overview

Why Parallel Programming?

Overview of OpenMP

Core Features of OpenMP

More Features and Details...

One Advanced Feature

Introduction

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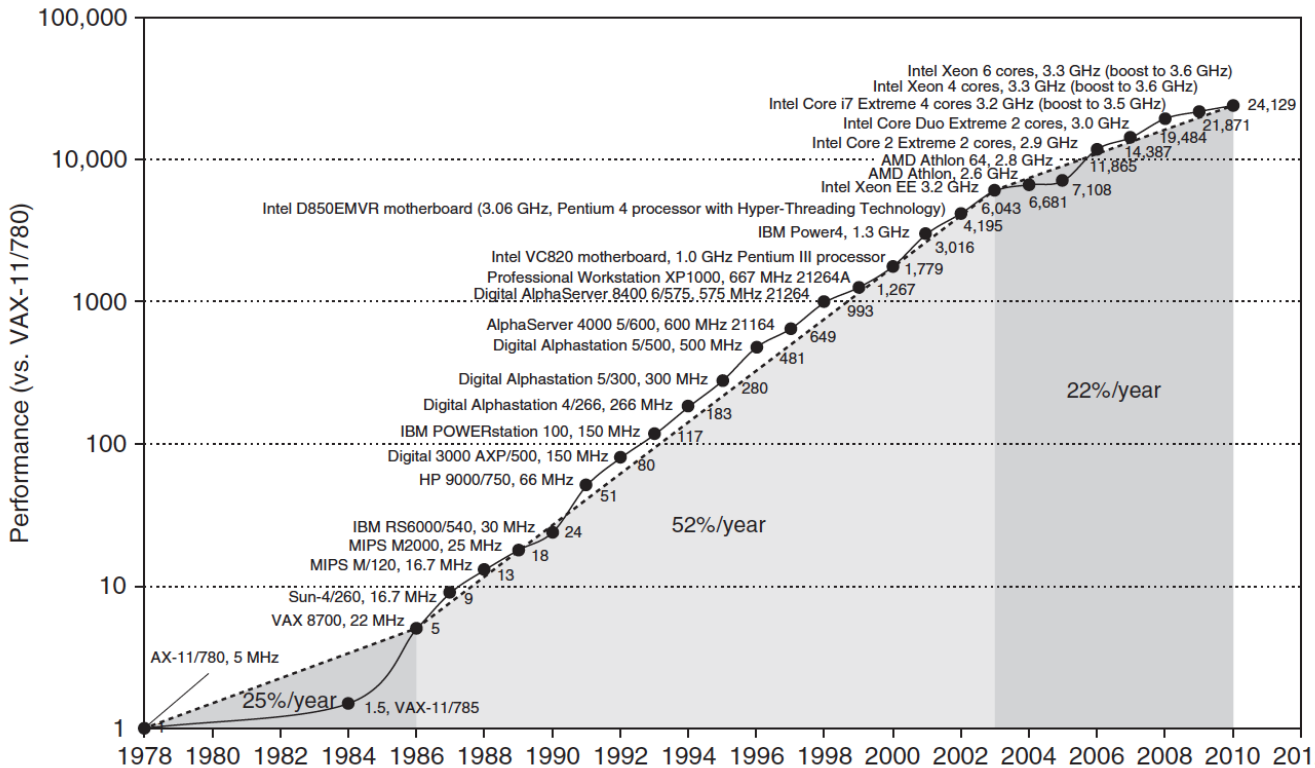
- It is relatively easy to use which makes a great language to start with when learning to write parallel programs
- Assumptions:
  - We assume you know C++ (OpenMP also supports Fortran)
  - We assume you are new to parallel programing
  - We assume you have access to a compiler that supports OpenMP (like gcc)

Why Parallel Programming?

Growth in processor performance since the late 1970s



Source: Hennessy, J. L., & Patterson, D. A. (2011). Computer architecture: a quantitative approach. Elsevier.

- Good old days: 17 years of sustained growth in performance at an annual rate of over 50%

The Hardware/Software Contract

- We (SW developers) learn and design sequential algorithms such as quick sort and Dijkstra's algorithm

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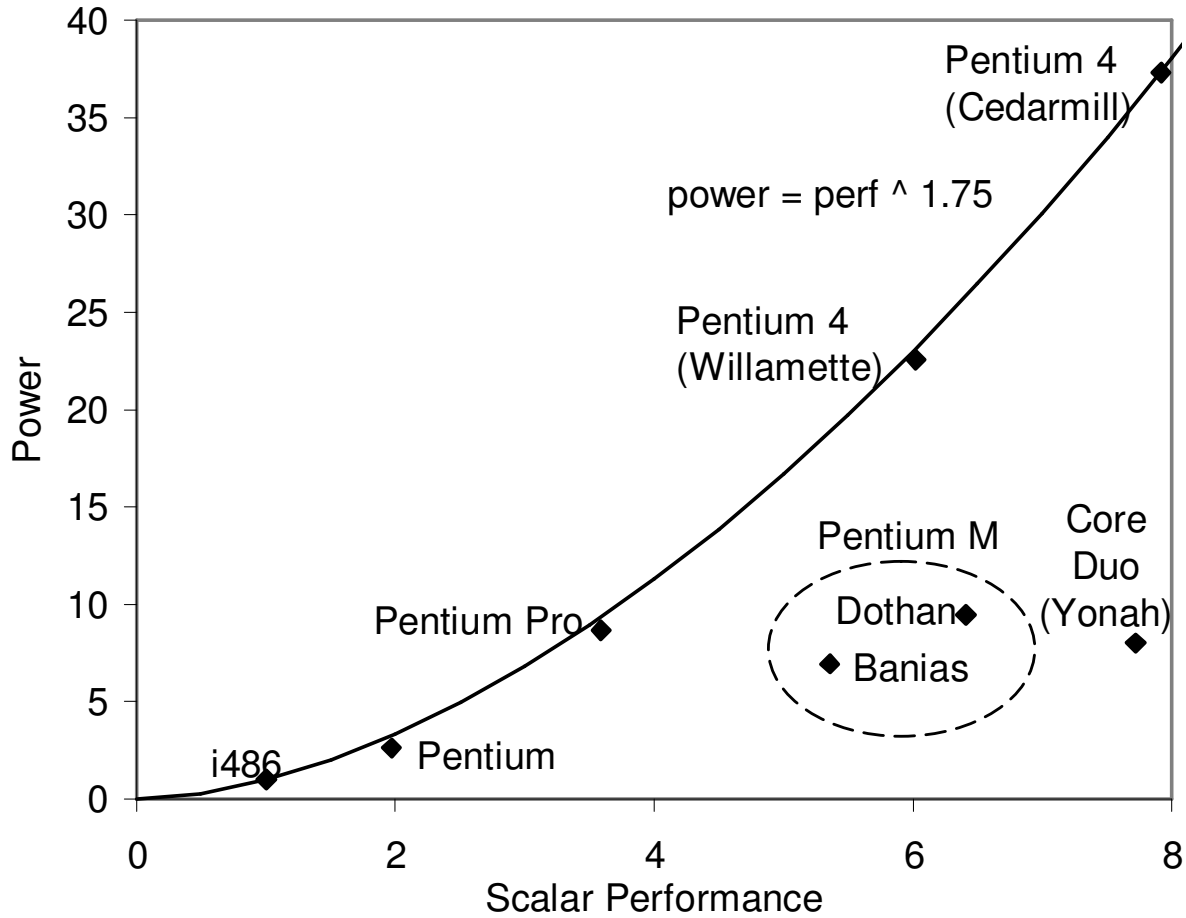
But...

- In 2004, Intel canceled its **high-performance uniprocessor projects** and joined others in declaring that the road to higher performance would be via **multiple processors per chip** rather than via **faster uniprocessors**

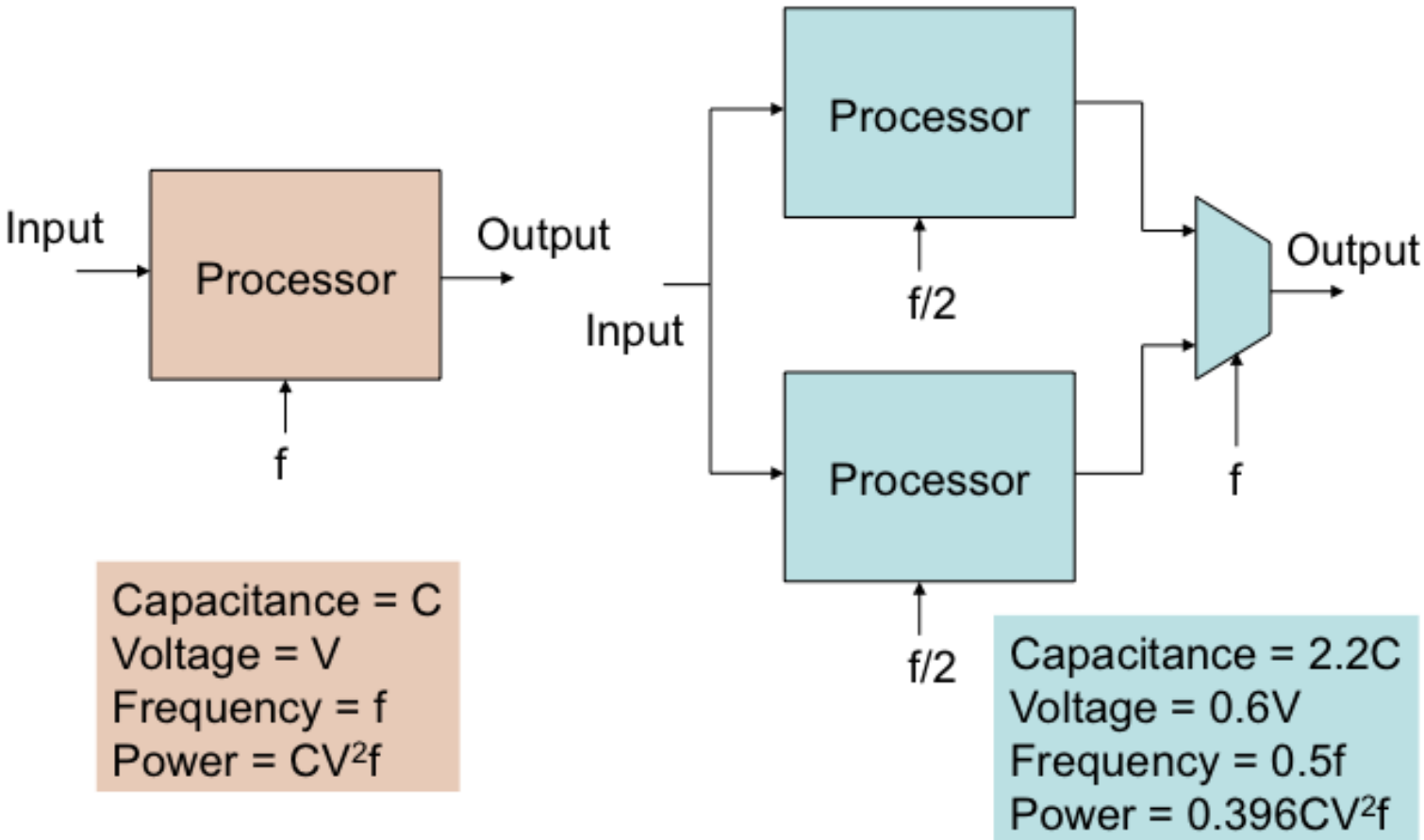
Computer Architecture and the Power Wall



Source: Grochowski, Ed, and Murali Annavaram. "Energy per instruction trends in Intel microprocessors." Technology@Intel Magazine 4, no. 3 (2006): 1-8.

- Growth in power is unsustainable (power $=$ perf$^{1.74}$)
- Partial solution: simple low power cores

The rest of the solution - Add Cores



Source: Multi-Core Parallelism for Low-Power Design - Vishwani D. Agrawal

Microprocessor Trends

Individual processors are **many core** (and often heterogeneous) processors from Intel, AMD, NVIDIA

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Microprocessor Trends

Individual processors are **many core** (and often heterogeneous) processors from Intel, AMD, NVIDIA
A new HW/SW contract:

- HW people will do what's natural for them (lots of simple cores) and SW people will have to adapt (rewrite everything)
- The problem is this was presented as an ultimatum... nobody asked us if we were OK with this new contract... which is kind of rude

Parallel Programming

Process:

1. We have a sequential algorithm
2. Split the program into tasks and identify shared and local data
3. Use some algorithm strategy to break dependencies between tasks
4. Implement the parallel algorithm in C++/Java/...

Can this process be automated by the compiler?
Unlikely... We have to do it manually.

Overview of OpenMP

OpenMP: Overview

OpenMP: an API for writing multi-threaded applications

- A set of compiler directives and library routines for parallel application programmers
- Greatly simplifies writing multi-threaded programs in Fortran and C/C++
- Standardizes last 20 years of symmetric multiprocessing (SMP) practice

OpenMP Core Syntax

- Most of the constructs in OpenMP are compiler directives:
  `#pragma omp <construct> [clause1 clause2 ...]`
- Example:
  `#pragma omp parallel num_threads(4)`
- Include file for runtime library: `#include <omp.h>`
- 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

Exercise 1: Hello World

A multi-threaded "hello world" program

```
1 #include <stdio.h>
2 #include <omp.h>
3 int main() {
4 #pragma omp parallel
5   {
6     int ID = omp_get_thread_num();
7     printf(" hello(%d)", ID);
8     printf(" world(%d)\n", ID);
9   }
10 }
```

Compiler Notes

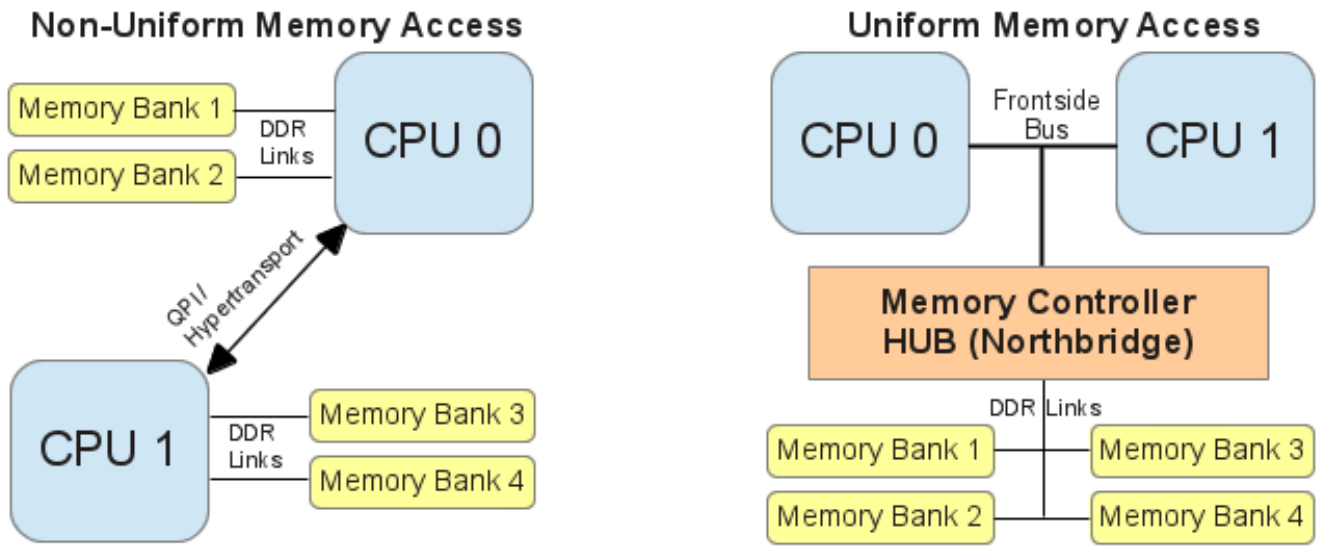
- On Windows, you can use Visual Studio C++ 2005 (or later) or Intel C Compiler 10.1 (or later)
- Linux and OS X with gcc (4.2 or later):

```
1 $ g++ hello.cpp -fopenmp # add -fopenmp to enable it
2 $ export OMP_NUM_THREADS=16 # set the number of threads
3 $ ./a.out # run our parallel program
```

- More information:
  `http://openmp.org/wp/openmp-compilers/`

Symmetric Multiprocessing (SMP)

- **A SMP system**: multiple identical processors connect to a single, shared main memory. Two classes:
  - **Uniform Memory Access (UMA)**: all the processors share the physical memory uniformly
  - **Non-Uniform Memory Access (NUMA)**: memory access time depends on the memory location relative to a processor



Source: `https://moinakg.wordpress.com/2013/06/05/findings-by-google-on-numa-performance/`

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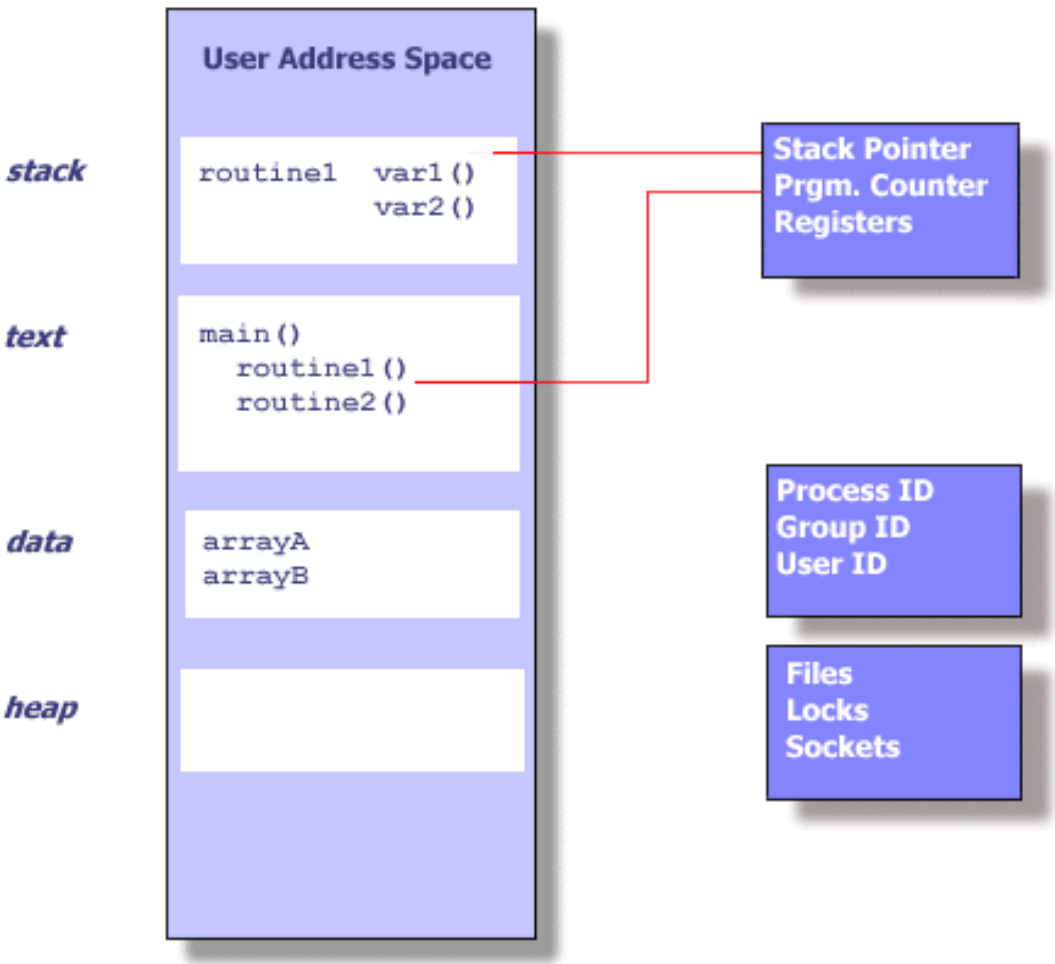
- Reality is more complex... Any multiprocessor CPU with a cache is a NUMA system

Symmetric Multiprocessing (SMP)

- SMP computers are everywhere... Most laptops and servers have multi-core multiprocessor CPUs
- The shared address space and (as we will see) programming models encourage us to think of them as UMA systems
- Reality is more complex... Any multiprocessor CPU with a cache is a NUMA system
- Start out by treating the system as a UMA and just accept that much of your optimization work will address cases where that case breaks down

SMP Programming

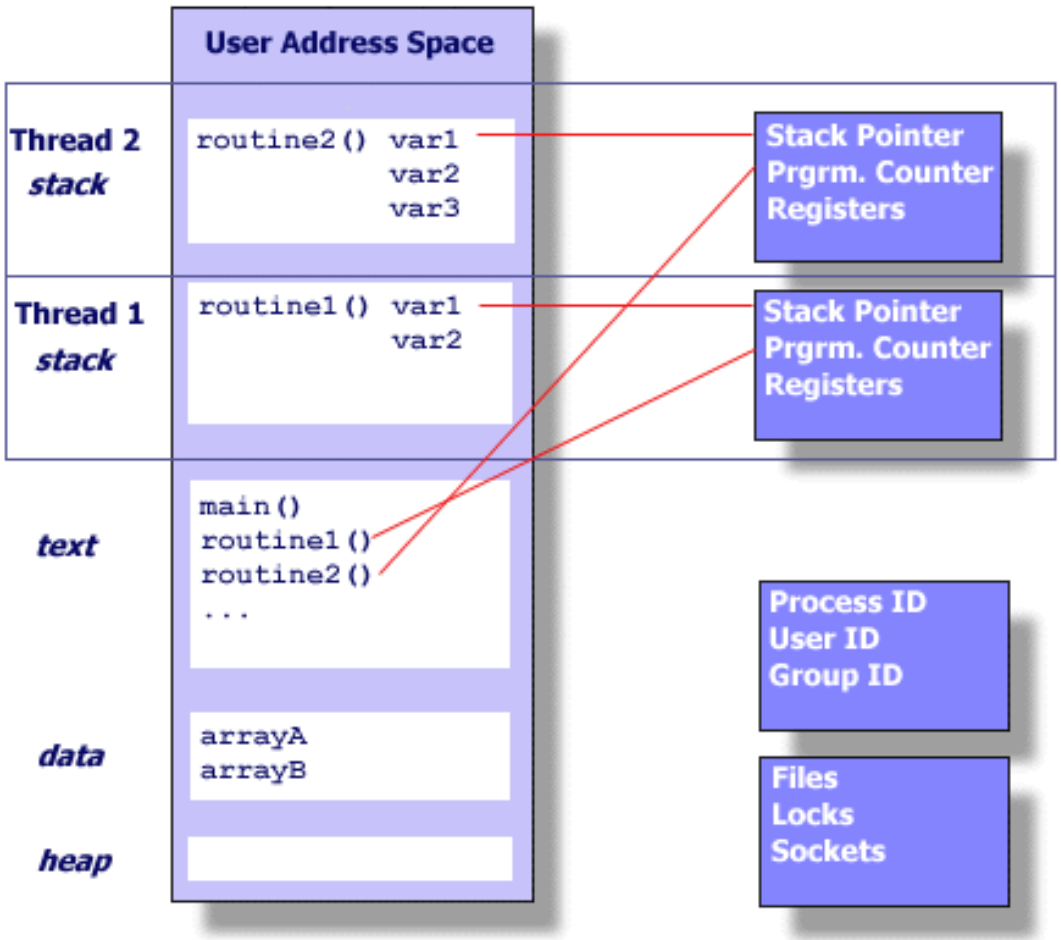


Source: `https://computing.llnl.gov/tutorials/pthreads/`

Process:

- an instance of a program execution
- contain information about program resources and program execution state

SMP Programming



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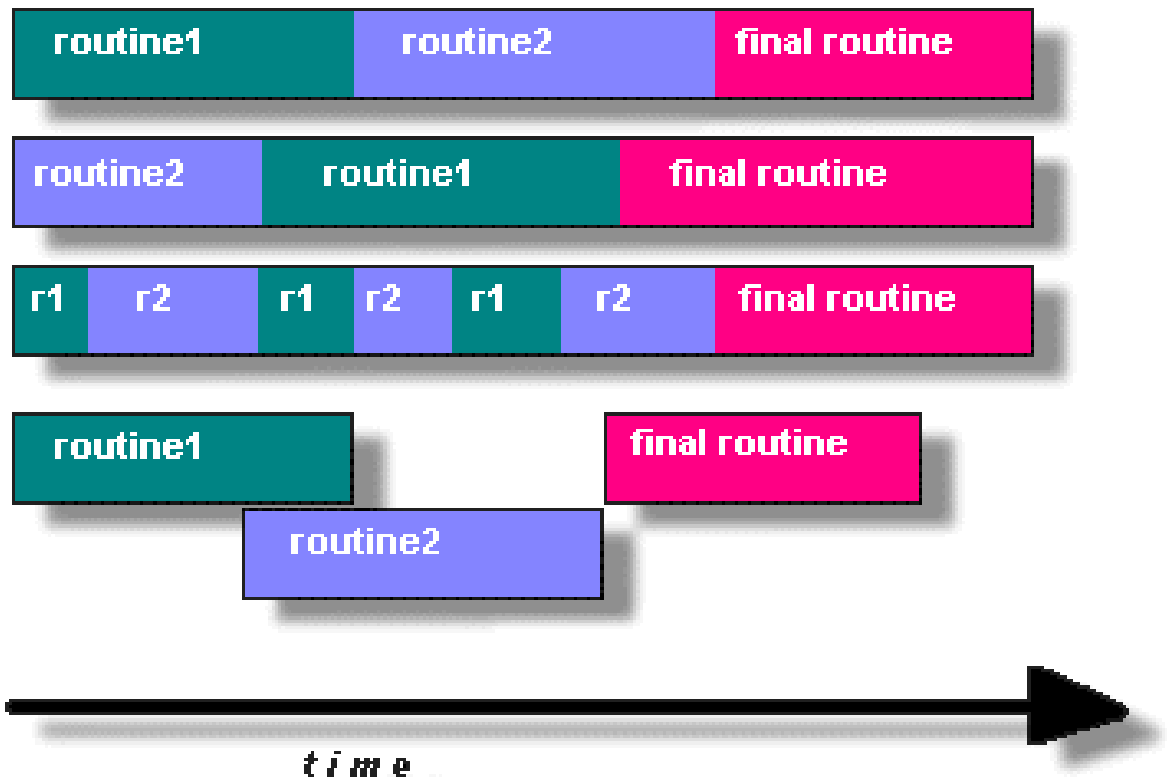
Threads:

- "light weight processes"
- share process state
- reduce the cost of swithcing context

Concurrency

Threads can be interchanged, interleaved and/or overlapped in real time.



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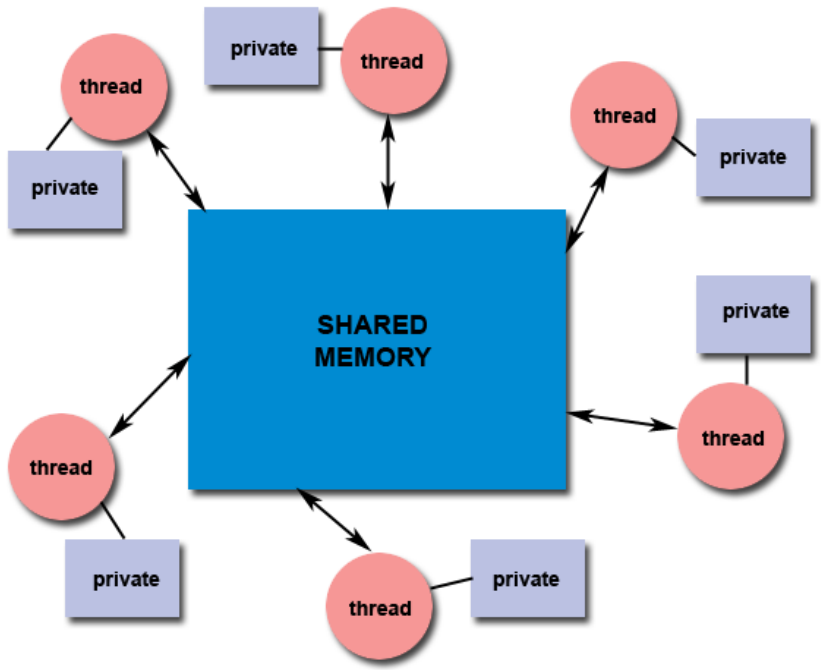
Shared Memory Model

- All threads have access to the same global, shared memory
- Threads also have their own private data
- Programmers are responsible for synchronizing access (protecting) globally shared data



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int main() {
#pragma omp parallel
  {
    int ID =
        omp_get_thread_num();
    printf(" hello(%d)", ID);
    printf(" world(%d)\n",
        ID);
  }
}
```

```
$ g++ hello.cpp -fopenmp
$ export OMP_NUM_THREADS=16
$ ./a.out
```

Sample Output:

```
hello(7) world(7)
hello(1) hello(9) world(9)
world(1)
hello(13) world(13)
hello(14) hello(4) hello(15)
    world(15)
world(4)
hello(2) world(2)
hello(10) world(10)
hello(11) world(11)
world(14)
hello(6) world(6)
hello(5) world(5)
hello(3) world(3)
hello(0) world(0)
hello(12) world(12)
hello(8) world(8)
```

Threads interleave and give different outputs every time

How Do Threads Interact in OpenMP?

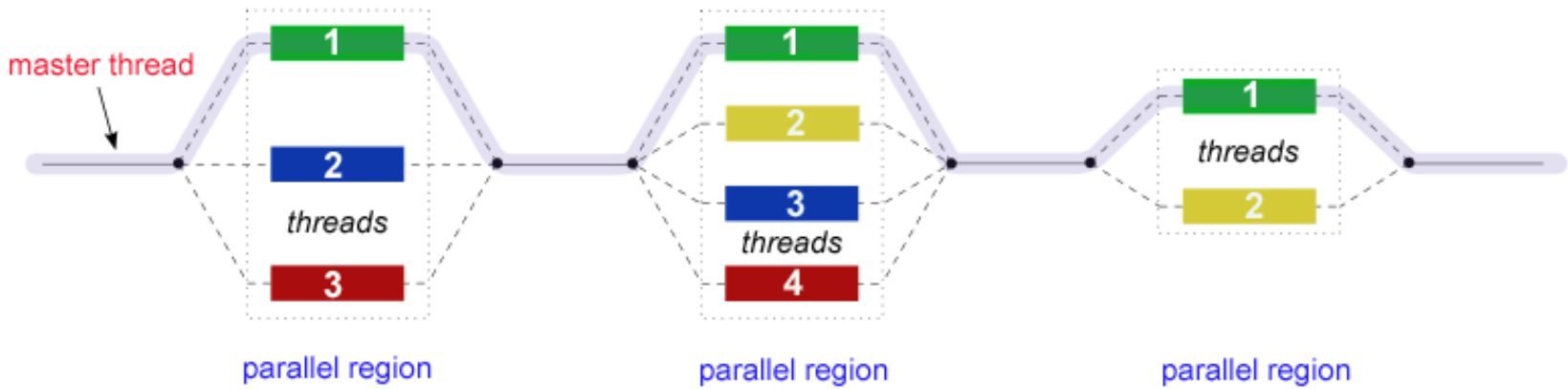
- OpenMP is a multi-threading, shared address model
  - Threads communicate by sharing variables
- Unintended sharing of data causes race conditions:
  - Race condition: when the program's outcome changes as the threads are scheduled differently
- To control race conditions:
  - Use synchronization to protect data conflicts
- Synchronization is expensive so:
  - Change how data is accessed to minimize the need for synchronization

Core Features of OpenMP

OpenMP Programming Model

Fork-Join Parallelism Model:

- OpenMP programs start with only the master thread
- FORK: the master thread creates a team of parallel threads when encounter a parallel region construct
- The parallel region construct are then executed in parallel
- JOIN: When the team threads complete, they synchronize and terminate, leaving only the master thread



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Thread Creation: Parallel Regions

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

```
1 double A[1000];
2 omp_set_num_threads(4); // declared in omp.h
3 #pragma omp parallel
4 {
5   int ID = omp_get_thread_num();
6   pooh(ID,A);
7 }
8 printf("all done\n");
```

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

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- For example, to create a 4-thread parallel region:

```
1 double A[1000];
2 // specify the number of threads using a clause
3 #pragma omp parallel num_threads(4)
4 {
5   int ID = omp_get_thread_num();
6   pooh(ID,A);
7 }
8 printf("all done\n");
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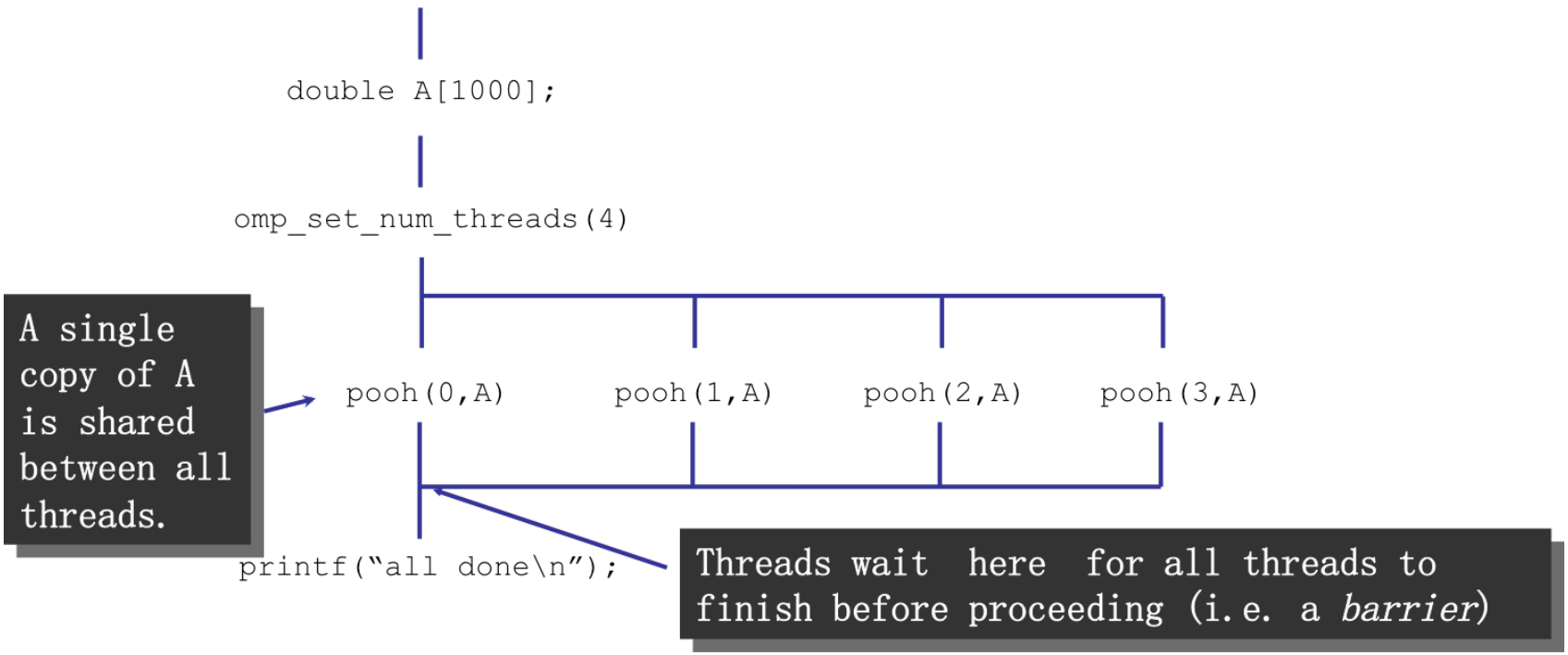
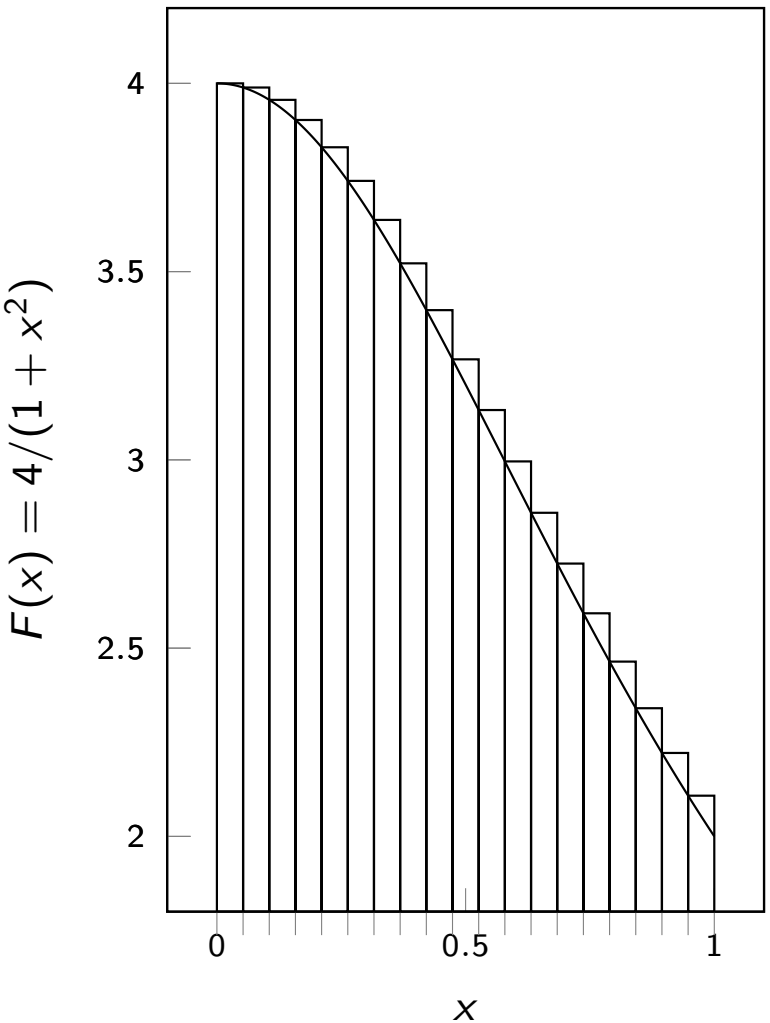


Compute π using Numerical Integration



Mathematically, we know that:

$$\int_0^1 \frac{4}{1+x^2} dx = \pi$$

We can approximate the integral as a sum of rectangles:

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

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

Serial π Program

```
1 #include <stdio.h>
2
3 const long num_steps = 100000000;
4
5 int main () {
6     double sum = 0.0;
7     double step = 1.0 / (double) num_steps;
8
9     for (int i = 0; i < num_steps; i++) {
10        double x = (i+0.5) * step;
11        sum += 4.0 / (1.0 + x*x);
12    }
13
14    double pi = step * sum;
15
16    printf("pi is %f \n", pi);
17 }
```

Exercise 2: First Prallel π Program

- Create a parallel version of the pi program using a parallel construct
- Pay close attention to shared versus private variables
- In addition to a parallel construct, you will need the runtime library routines
  - `int omp_get_num_threads()`: number of threads in the team
  - `int omp_get_thread_num()`: ID of current thread

Exercise 2: First Prallel π Program

```
 1 #include <stdio.h>
 2 #include <omp.h>
 3 const long num_steps = 100000000;
 4 #define NUM_THREADS 4
 5 double sum[NUM_THREADS];
 6 int main () {
 7     double step = 1.0 / (double) num_steps;
 8     omp_set_num_threads(NUM_THREADS);
 9 #pragma omp parallel
10     {
11         int id = omp_get_thread_num();
12         sum[id] = 0.0;
13         for (int i = id; i < num_steps; i += NUM_THREADS) {
14             double x = (i+0.5) * step;
15             sum[id] += 4.0 / (1.0 + x*x);
16         }
17     }
18     double pi = 0.0;
19     for (int i = 0; i < NUM_THREADS; i++)
20         pi += sum[i] * step;
21     printf("pi is %f \n", pi);
22 }
```

Algorithm Strategy: SPMD

The SPMD (single program, multiple data) technique:

- Run the same program on P processing elements where P can be arbitrarily large
- Use the rank (an ID ranging from 0 to $P - 1$) to select between a set of tasks and to manage any shared data structures

This pattern is very general and has been used to support most (if not all) parallel software.

Results

- Setup: gcc with no optimization on Ubuntu 14.04 with a quad-core Intel(R) Xeon(R) CPU E5-1620 v2 @ 3.70GHz and 16 GB RAM
- The serial version ran in 1.25 seconds

Threads	1	2	3	4
SPMD	1.29	0.72	0.47	0.48

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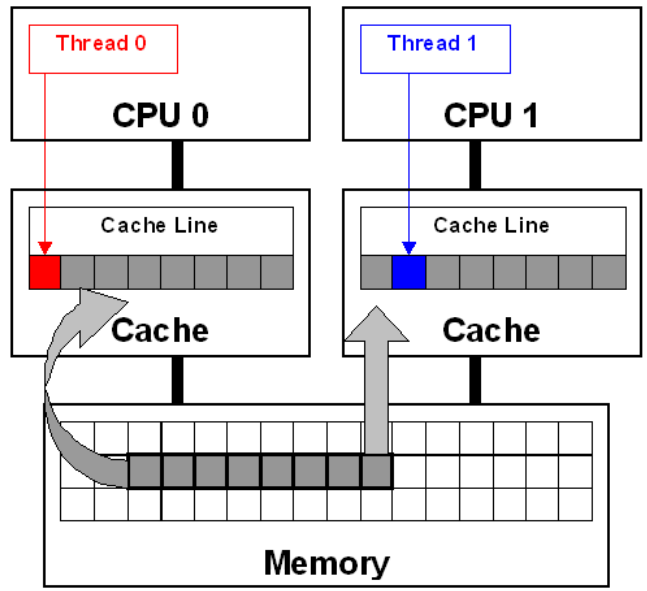
Why such poor scaling?

Reason: 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"**



Source: `https://software.intel.com/en-us/articles/avoiding-and-identifying-false-sharing-among-threads`

- Solution: pad arrays so elements you use are on distinct cache lines

Eliminate False Sharing by Padding

```
1 #include <stdio.h>
2 #include <omp.h>
3 const long num_steps = 100000000;
4 #define NUM_THREADS 4
5 #define PAD         8 // assume 64bbytes L1 cache
6 double sum[NUM_THREADS][PAD];
7 int main () {
8     double step = 1.0 / (double) num_steps;
9     omp_set_num_threads(NUM_THREADS);
10 #pragma omp parallel
11     {
12         int id = omp_get_thread_num();
13         sum[id][0] = 0.0;
14         for (int i = id; i < num_steps; i += NUM_THREADS) {
15             double x = (i+0.5) * step;
16             sum[id][0] += 4.0 / (1.0 + x*x);
17         }
18     }
19     double pi = 0.0;
20     for (int i = 0; i < NUM_THREADS; i++)
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23 }
```

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SPMD	1.29	0.72	0.47	0.48
Padding	1.27	0.65	0.43	0.33

Do We Really Need to Pad Our Arrays?

- Padding arrays requires deep knowledge of the cache architecture
- Move to a machine with different sized cache lines and your software performance falls apart
- There has got to be a better way to deal with false sharing

High Level Synchronization

Recall: to control race conditions

- use synchronization to protect data conflicts

Synchronization: bringing one or more threads to a well defined and known point in their execution

- **Barrier**: each thread wait at the barrier until all threads arrive
- **Mutual exclusion**: define a block of code that only one thread at a time can execute

Synchronization: barrier

Barrier: each thread wait until all threads arrive

```
1 #pragma omp parallel
2 {
3   int id = omp_get_thread_num();
4   A[id] = big_calc1(id);
5 #pragma omp barrier
6   B[id] = big_calc2(id, A); // depend on A calculated by
        every thread
7 }
```

Synchronization: critical

Mutual exclusion: define a block of code that only one thread at a time can execute

```
1  float res;
2  #pragma omp parallel
3  {
4    float B; int i, id, nthrds;
5    id = omp_get_thread_num();
6    nthrds = omp_get_num_threads();
7    for (i = id; i < niters; i += nthrds) {
8      B = big_job(i);
9  #pragma omp critical
10     res += consume(B);
11     // only one at a time calls consume() and modify res
12   }
13 }
```

Synchronization: atomic

Atomic provides mutual exclusion but only applies to the update of a memory location and only supports `x += expr`, `x++`, `--x`...

```
1 float res;
2 #pragma omp parallel
3 {
4   float tmp, B;
5   B = big();
6   tmp = calc(B);
7 #pragma omp atomic
8   res += tmp;
9 }
```

Exercise 3: Rewrite π Program using Synchronization

```
 1 #include <stdio.h>
 2 #include <omp.h>
 3 const long num_steps = 100000000;
 4 #define NUM_THREADS 4
 5 int main () {
 6     double step = 1.0 / (double) num_steps;
 7     omp_set_num_threads(NUM_THREADS);
 8     double pi = 0.0;
 9 #pragma omp parallel
10     {
11         int id = omp_get_thread_num();
12         double sum = 0.0; // local scalar not array
13         for (int i = id; i < num_steps; i += NUM_THREADS) {
14             double x = (i+0.5) * step;
15             sum += 4.0 / (1.0 + x*x); // no false sharing
16         }
17 #pragma omp critical
18         pi += sum * step; // must do summation here
19     }
20     printf("pi is %f \n", pi);
21 }
```

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Threads	1	2	3	4
SPMD	1.29	0.72	0.47	0.48
Padding	1.27	0.65	0.43	0.33
Critical	1.26	0.65	0.44	0.33

Mutal Exclusion Done Wrong

Be careful where you put a critical section.

```
1 #include <stdio.h>
2 #include <omp.h>
3 const long num_steps = 100000000;
4 #define NUM_THREADS 4
5 int main () {
6     double step = 1.0 / (double) num_steps;
7     omp_set_num_threads(NUM_THREADS);
8     double pi = 0.0;
9 #pragma omp parallel
10    {
11        int id = omp_get_thread_num();
12        for (int i = id; i < num_steps; i += NUM_THREADS) {
13            double x = (i+0.5) * step;
14 #pragma omp critical
15            pi += 4.0 / (1.0 + x*x) * step;
16        }
17    }
18    printf("pi is %f \n", pi);
19 }
```

Ran in 10 seconds with 4 threads.

Example: Using Atomic

```
 1 #include <stdio.h>
 2 #include <omp.h>
 3 const long num_steps = 100000000;
 4 #define NUM_THREADS 4
 5 int main () {
 6     double step = 1.0 / (double) num_steps;
 7     omp_set_num_threads(NUM_THREADS);
 8     double pi = 0.0;
 9 #pragma omp parallel
10     {
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12         double sum = 0.0;
13         for (int i = id; i < num_steps; i += NUM_THREADS) {
14             double x = (i+0.5) * step;
15             sum += 4.0 / (1.0 + x*x);
16         }
17         sum *= step;
18 #pragma omp atomic
19         pi += sum;
20     }
21     printf("pi is %f \n", pi);
22 }
```

For Loop Worksharing

Serial π program:

```
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13
14    double pi = step * sum;
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16    printf("pi is %f \n", pi);
17 }
```

What we want to parallelize:

```
for (int i = 0; i < num_steps; i++)
```

For Loop Worksharing

Two equivalent directives:

```
1 double res[MAX];
2 #pragma omp parallel
3 {
4 #pragma omp for
5   for (int i = 0; i < MAX;
        i++)
6     res[i] = huge();
7 }
```

```
1 double res[MAX];
2 #pragma omp parallel for
3   for (int i = 0; i < MAX;
        i++)
4     res[i] = huge();
```

Working with For Loops

- Find computational intensive loops
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```
1 int j, A[MAX];
2 j = 5;
3 for (int i = 0; i < MAX; i++)
      {
4   j += 2;
5   A[i] = big(j);
6 }
```

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      {
4   j += 2;
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6 }
```

Each iteration depends on the preivous one.

```
1 int A[MAX];
2 #pragma omp parallel for
3 for (int i = 0; i < MAX; i++)
      {
4   int j = 5 + 2*(i+1);
5   A[i] = big(j);
6 }
```

Remove dependency and j is now local to each iteration.

The Schdule Clause

The schedule clause affects how loop iterations are mapped onto threads

- `schedule(static, [chunk])`: each thread independently decides which which iterations of size "chunk" they will process
- `schedule(dynamic, [chunk])`: each thread grabs "chunk" iterations off a queue until all iterations have been handled
- guided, runtime, auto: skip...

Nested Loops

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

```
1 #pragma omp parallel for collapse(2)
2 for (int i = 0; i < N; i++) {
3   for (int j=0; j<M; j++) {
4     .....
5   }
6 }
```

- Will form a single loop of length $N \times M$ and then parallelize that
- Useful if N is O(num of threads) so parallelizing the outer loop makes balancing the load difficult

Reduction

- How do we handle this case?

```
1 double ave=0.0, A[MAX];
2 for (int i = 0; i < MAX; i++) {
3   ave += A[i];
4 }
5 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 such as MapReduce and MPI

Reduction

- OpenMP reduction clause: `reduction(op:list)`
- Inside a parallel or a worksharing 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

```
1 double ave=0.0, A[MAX];
2 #pragma omp parallel for reduction(+:ave)
3 for (int i = 0; i < MAX; i++) {
4   ave += A[i];
5 }
6 ave = ave/MAX;
```

Exercise 4: π Program with Parallel For

```
1 #include <stdio.h>
2 #include <omp.h>
3 const long num_steps = 100000000;
4 #define NUM_THREADS 4
5 int main () {
6     double sum = 0.0;
7     double step = 1.0 / (double) num_steps;
8     omp_set_num_threads(NUM_THREADS);
9 #pragma omp parallel for reduction(+:sum)
10    for (int i = 0; i < num_steps; i++) {
11        double x = (i+0.5) * step;
12        sum += 4.0 / (1.0 + x*x);
13    }
14    double pi = step * sum;
15    printf("pi is %f \n", pi);
16 }
```

Quite simple...

Results

- Setup: gcc with no optimization on Ubuntu 14.04 with a quad-core Intel(R) Xeon(R) CPU E5-1620 v2 @ 3.70GHz and 16 GB RAM
- The serial version ran in 1.25 seconds

Threads	1	2	3	4
SPMD	1.29	0.72	0.47	0.48
Padding	1.27	0.65	0.43	0.33
Critical	1.26	0.65	0.44	0.33
For	1.27	0.65	0.43	0.33

More Features and Details...

Synchronization: barrier

Barrier: each thread wait until all threads arrive

```
1 #pragma omp parallel
2 {
3   id=omp_get_thread_num();
4   A[id] = big_calc1(id);
5 #pragma omp barrier
6 #pragma omp for
7   for (int i = 0; i < N; i++) {
8     C[i] = big_calc3(i, A);
9   } // implicit barrier at the end of a for workesharing
        construct
10 #pragma omp for nowait
11   for (int i = 0; i < N; i++) {
12     B[i] = big_calc2(C, i);
13   } // no implicit barrier due to nowait
14   A[id] = big_calc4(id);
15 } // implicit barrier at the end of a parallel region
```

Master Construct

- The master construct denotes a structured block that is only executed by the master thread
- The other threads just skip it (no synchronization is implied)

```
1 #pragma omp parallel
2 {
3   do_many_things();
4 #pragma omp master
5   { exchange_boundaries(); }
6 #pragma omp barrier
7   do_many_other_things();
8 }
```

Single Construct

- The single construct denotes a structured block that is only executed by only one thread
- A barrier is implied at the end of the single block (can remove the barrier with a *nowait* clause)

```
1 #pragma omp parallel
2 {
3   do_many_things();
4 #pragma omp single
5   { exchange_boundaries(); }
6   do_many_other_things();
7 }
```

Low Level Synchronization: lock routines

- Simple lock routines: a simple lock is available if it is unset

  `omp_init_lock()`, `omp_set_lock()`, `omp_unset_lock()`, `omp_test_lock()`, `omp_destroy_lock()`

- Nested locks: a nested lock is available if it is unset or if it is set but owned by the thread executing the nested lock function

  `omp_init_nest_lock()`, `omp_set_nest_lock()`, `omp_unset_nest_lock()`, `omp_test_nest_lock()`, `omp_destroy_nest_lock()`

Synchronization: Simple Locks

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

```
1 #pragma omp parallel for
2     for (int i = 0; i < NBUCKETS; i++) {
3         omp_init_lock(&hist_locks[i]); // one lock per
              elements of hist
4         hist[i] = 0;
5     }
6 #pragma omp parallel for
7     for(int i = 0; i < NVALS; i++) {
8         ival = (int) sample(arr[i]);
9         omp_set_lock(&hist_locks[ival]);
10            hist[ival]++; // mutual exclusion, less wait
                  compared to critical
11        omp_unset_lock(&hist_locks[ival]);
12    }
13 #pragma omp parallel for
14    for(i=0;i<NBUCKETS; i++)
15        omp_destroy_lock(&hist_locks[i]); // free locks
              when done
```

Sections Worksharing

- The sections worksharing construct gives a different structured block to each thread

```
1 #pragma omp parallel
2 {
3 #pragma omp sections
4   {
5 #pragma omp section
6     x_calculation();
7 #pragma omp section
8     y_calculation();
9 #pragma omp section
10    z_calculation();
11  } // implicit barrier that can be turned off with nowait
12 }
```

Shorthand: `#pragma omp parallel sections`

Runtime Library Routines

- Modify/Check the number of threads - `omp_set_num_threads()`, `omp_get_num_threads()`, `omp_get_thread_num()`, `omp_get_max_threads()`
- Are we in an active parallel region? - `omp_in_parallel()`
- How many processors in the system? - `omp_num_procs()`
- Many less commonly used routines

Data Sharing

- Most variables are SHARED by default: static variables, global variables, heap data (`malloc()`, `new`)
- But not everything is shared: stack variables in functions called from parallel regions are PRIVATE

Examples:

```
1 double A[10];
2 int main() {
3     int index[10];
4 #pragma omp parallel
5     work(index);
6     printf("%d\n", index[0]);
7 }
```

```
1 extern double A[10];
2 void work(int *index) {
3     double temp[10];
4     static int count;
5     // do something
6 }
```

`A`, `index`, `count` are shared.

`temp` is private to each thread.

Data Scope Attribute Clauses

- Change scope attributes using:
  `shared, private, firstprivate, lastprivate`
- The default attributes can be overridden with:
  `default(shared|none)`
- Skip details...

Data Scope Attribute Clauses: Example

```
1  int main() {
2      std::string a = "a", b = "b", c = "c";
3  #pragma omp parallel firstprivate(a) private(b) shared(c)
       num_threads(2)
4      {
5          a += "k"; // a is initialized with "a"
6          b += "k"; // b is initialized with std::string()
7  #pragma omp critical
8          {
9              c += "k"; // c is shared
10             std::cout << omp_get_thread_num() << ": " << a
                   << ", " << b << ", " << c << "\n";
11         }
12     }
13     std::cout << a << ", " << b << ", " << c << "\n";
14 }
```

Sample Output:

```
1 0: ak, k, ck
2 1: ak, k, ckk
3 a, b, ckk
```

One Advanced Feature

OpenMP Tasks

- The for and sections worksharings worked well for many cases. However,
  - loops need a known length at run time
  - finite number of parallel sections
- This didn't work well with certain common problems:
  - linked list, recursive algorithms, etc.
- Introduce the task directive (only for OpenMP 3.0+)

Task: Example

Traversal of a tree:

```
1  struct node { node *left, *right; };
2  extern void process(node* );
3  void traverse(node* p) {
4      if (p->left)
5  #pragma omp task // p is firstprivate by default
6          traverse(p->left);
7      if (p->right)
8  #pragma omp task // p is firstprivate by default
9          traverse(p->right);
10     process(p);
11 }
```

```
1 #pragma omp parallel
2 {
3     #pragma omp single nowait
4     { traverse(root); }
5 }
```

Task: Example

What if we want to force a postorder traversal of the tree?

```
1  struct node { node *left, *right; };
2  extern void process(node* );
3  void traverse(node* p) {
4      if (p->left)
5  #pragma omp task // p is firstprivate by default
6          traverse(p->left);
7      if (p->right)
8  #pragma omp task // p is firstprivate by default
9          traverse(p->right);
10 #pragma omp taskwait // a barrier only for tasks
11     process(p);
12 }
```

Task: Example

Process elements of a linked list in parallel:

```
1  struct node { int data; node* next; };
2  extern void process(node* );
3  void increment_list_items(node* head) {
4      #pragma omp parallel
5      {
6          #pragma omp single
7          {
8              for(node* p = head; p; p = p->next) {
9                  #pragma omp task
10                 process(p); // p is firstprivate by default
11             }
12         }
13     }
14 }
```

References

- Guide into OpenMP: Easy multithreading programming for C++: `http://bisqwit.iki.fi/story/howto/openmp`
- Introduction to OpenMP - Tim Mattson (Intel):
  - slides: `http://openmp.org/mp-documents/Intro_To_OpenMP_Mattson.pdf`
  - videos: `https://www.youtube.com/playlist?list=PLLX-Q6B8xqZ8n8bwjGdzBJ25X2utwnoEG`
- OpenMP specification: `http://openmp.org`