CS 61C: Great Ideas in Computer Architecture (Machine Structures)
Thread Level Parallelism: OpenMP

Instructor:
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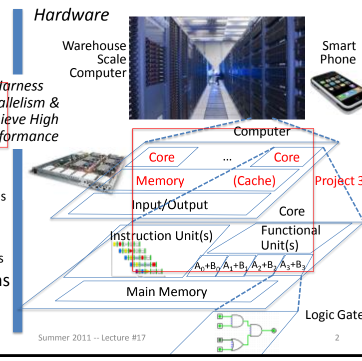
You Are Here!

Software

- Parallel Requests
  Assigned to computer
  e.g., Search "Katz"
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Add of 4 pairs of words
- Hardware descriptions
  All gates functioning in parallel at same time

Harness Parallelism & Achieve High Performance



Peer Instruction: Synchronization

- Consider the following code when executed concurrently by two threads:

```
lw $t0,0($s0)
addi $t0,$t0,1
sw $t0,0($s0)

(Mem[$s0] contains value 100)
```

Green)	100, 101, or 102
Blue)	101 or 102
Yellow)	100 or 102
Red)	100 or 101
Purple)	102

- What possible values can result in Mem[$s0]?

Peer Instruction: Synchronization, Answer

- Consider the following code when executed concurrently by two threads:

```
lw $t0,0($s0)
addi $t0,$t0,1
sw $t0,0($s0)

(Mem[$s0] contains value 100)
```

Green)	100, 101, or 102
Blue)	101 or 102
Yellow)	100 or 102
Red)	100 or 101
Purple)	102

- What possible values can result in Mem[$s0]?

- 102 if one thread starts executing after the other completely finishes.
- 101 if both threads execute the lw before either thread executes the sw. One thread will see "stale data"

Lock and Unlock Synchronization

- Lock used to create region (*critical section*) where only one thread can operate
- Given shared memory, use memory location as synchronization point: the *lock*
- Processors read lock to see if must wait, or OK to go into critical section (and set to locked)
  - 0 => lock is free / open / unlocked / lock off
  - 1 => lock is set / closed / locked / lock on

```
Set the lock
Critical section
  (only one thread
  gets to execute
  this section of
  code at a time)
e.g., change shared
  variables
Unset the lock
```

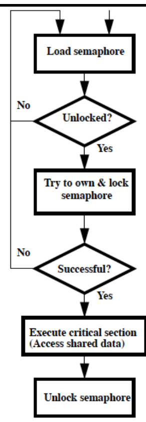

Synchronization in MIPS

- Load linked: `ll rt,offset(rs)`
- Store conditional: `sc rt,offset(rs)`
  - Succeeds if location not changed since the `ll`
    - Returns 1 in rt (clobbers register value being stored)
  - Fails if location has changed
    - Returns 0 in rt (clobbers register value being stored)
- Example: atomic swap (to test/set lock variable)
  Exchange contents of reg and mem: $s4 ←→ ($s1)

```
try: add $t0,$zero,$s4 ;copy exchange value
     ll  $t1,0($s1)    ;load linked
     sc  $t0,0($s1)    ;store conditional
     beq $t0,$zero,try ;branch store fails
     add $s4,$zero,$t1 ;put load value in $s4
```

Test-and-Set

- In a single atomic operation:
  - *Test* to see if a memory location is set (contains a 1)
  - *Set* it (to 1) If it isn't (it contained a zero when tested)
  - Otherwise indicate that the Set failed, so the program can try again
  - No other instruction can modify the memory location, including another Test-and-Set instruction
- Useful for implementing lock operations



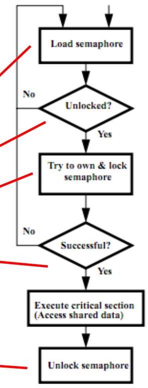
Test-and-Set in MIPS

- Example: MIPS sequence for implementing a T&S at ($s1)

```
Try: addiu $t0,$zero,1
     ll   $t1,0($s1)
     bne  $t1,$zero,Try
     sc   $t0,0($s1)
     beq  $t0,$zero,try
Locked:

     critical section

     sw $zero,0($s1)
```



Agenda

- OpenMP Introduction
- Administrivia
- OpenMP Examples
- Break
- Common Pitfalls
- Summary

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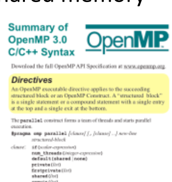
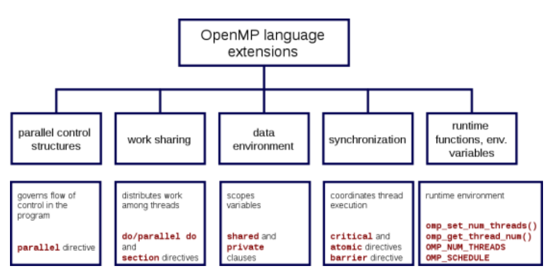
What is OpenMP?

- API used for multi-threaded, shared memory parallelism
  - Compiler Directives
  - Runtime Library Routines
  - Environment Variables
- Portable
- Standardized
- See http://www.openmp.org/, http://computing.llnl.gov/tutorials/openMP/



OpenMP Specification



Shared Memory Model with Explicit Thread-based Parallelism

- Multiple threads in a shared memory environment, explicit programming model with full programmer control over parallelization
- Pros:
  - Takes advantage of shared memory, programmer need not worry (that much) about data placement
  - Programming model is "serial-like" and thus conceptually simpler than alternatives (e.g., message passing/MPI)
  - Compiler directives are generally simple and easy to use
  - Legacy serial code does not need to be rewritten
- Cons:
  - Code can only be run in shared memory environments!
  - Compiler must support OpenMP (e.g., gcc 4.2)

OpenMP Built On C's "pragma" Mechanism

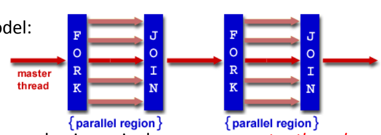
- Pragmas are a preprocessor mechanism that C provides for language extensions
- Many different uses: structure packing, symbol aliasing, floating point exception modes, …
- Example:

```
#pragma omp parallel for
```

- Good for OpenMP because compilers that don't recognize a pragma are supposed to ignore them
  - Runs on sequential computer even with embedded pragmas

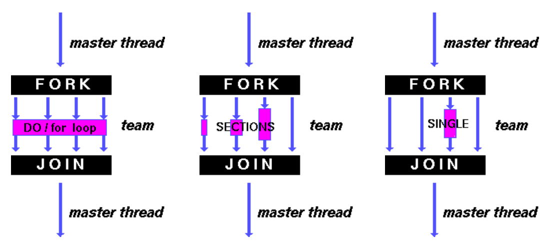
OpenMP Programming Model

- Fork - Join Model:



- OpenMP programs begin as single process: *master thread*; Executes sequentially until the first parallel region construct is encountered
  - FORK: the master thread then creates a team of parallel threads
  - Statements in program that are enclosed by the parallel region construct are executed in parallel among the various team threads
  - JOIN: When the team threads complete the statements in the parallel region construct, they synchronize and terminate, leaving only the master thread

OpenMP Directives



shares iterations of a loop across the team

each section executed by a separate thread

serializes the execution of a thread

Example: C `for` loop

```
for (i=0; i<max; i++) zero[i] = 0;
```

- Break *for loop* into chunks, and allocate each to a separate thread
  - E.g., if max = 100, with two threads, assign 0-49 to thread 0, 50-99 to thread 1
- Must have relatively simple "shape" for an OpenMP-aware compiler to be able to parallelize it
  - Necessary for the run-time system to be able to determine how many of the loop iterations to assign to each thread
- No premature exits from the loop allowed
  - i.e., No break, return, exit, goto statements

OpenMP: Parallel `for` *pragma*

```
#pragma omp parallel for
for (i=0; i<max; i++) zero[i] = 0;
```

- Master thread creates additional threads, each with a separate execution context
- All variables declared outside for loop are shared by default, except for loop index which is *private* per thread (Why?)
- Implicit synchronization at end of for loop
- Divide index regions sequentially per thread
  - Thread 0 gets 0, 1, …, (max/n)-1;
  - Thread 1 gets max/n, max/n+1, …, 2*(max/n)-1
  - Why?

Student Roulette?

Thread Creation

- How many threads will OpenMP create?
- Defined by OMP_NUM_THREADS environment variable (or in code procedure call)
- Set this variable to the maximum number of threads you want OpenMP to use
- Usually equals the number of cores in the underlying HW on which the program is run

OMP_NUM_THREADS

- Shell command to set number threads:
  `export OMP_NUM_THREADS=x`
- Shell command check number threads:
  `echo $OMP_NUM_THREADS`
- OpenMP intrinsic to set number of threads:
  `omp_num_threads(x);`
- OpenMP intrinsic to get number of threads:
  `num_th = omp_get_num_threads();`
- OpenMP intrinsic to get Thread ID number:
  `th_ID = omp_get_thread_num();`

"parallel" Statement and Scope

- The general parallel construct: Each thread executes a copy of the code within the block below.

```
#pragma omp parallel
{
   ID = omp_get_thread_num();
   foo(ID);
}
```

- OpenMP default is shared variables
  - To make private, need to declare with pragma

```
#pragma omp parallel private (x)
```


Parallel Statement Shorthand

```
#pragma omp parallel
{
  #pragma omp for  //This is the only
                   //directive in the
                   // parallel section
  for(i=0;i<len;i++) { … }
}
```

can be shortened to

```
#pragma omp parallel for
for(i=0;i<len;i++) { … }
```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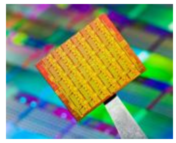
Administrivia

- Project #2: Matrix Multiply Performance Improvement
  - Work in groups of two!
  - Part 1: Due July 24 (this Sunday)
  - Part 2: Due July 31
- HW #3 also due July 27
- Closely packed due dates, try to get ahead of schedule for the project.

cs61c in the News

- Intel reveals new 50 core Knight's Corner co-processor, to compete with Nvidia's multi-hundred core "general purpose" Tesla GPU.
- "The main advantage that Intel touts vs. Tesla is that because MIC is just a bunch of x86 cores, it's easy for users to port their existing toolchains to it."



http://arstechnica.com/business/news/2011/06/intel-takes-wraps-off-of-50-core-supercomputing-coprocessor-plans.ars

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OpenMP Examples

- Hello World
- ~~OMP Get Environment~~ (hidden slides)
- For Loop Workshare
- Section Workshare
- Sequential and Parallel Numerical Calculation of Pi

Hello World in OpenMP

```
#include <omp.h>
#include <stdio.h>
int main (void) {
int nthreads, tid;
/* Fork team of threads with each having a private tid variable
   */
#pragma omp parallel private(tid)
   {
      /* Obtain and print thread id */
      tid = omp_get_thread_num();
      printf("Hello World from thread = %d\n", tid);
      /* Only master thread does this */
      if (tid == 0) {
         nthreads = omp_get_num_threads();
         printf("Number of threads = %d\n", nthreads);
      }
   }  /* All threads join master thread and terminate */
}
```


Hello World in OpenMP

```
localhost:OpenMP randykatz$ ./omp_hello
Hello World from thread = 0
Hello World from thread = 1
Number of threads = 2
```


Get Environment Information in OpenMP

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
int main (int argc, char *argv[])
{int nthreads, tid, procs, maxt, inpar, dynamic, nested;
   #pragma omp parallel private(nthreads, tid)
   {
     tid = omp_get_thread_num(); /* Obtain thread number */
     if (tid == 0) { /* Only master thread does this */
        printf("Thread %d getting environment info...\n", tid);
         /* Get environment information */
        procs = omp_get_num_procs();
        nthreads = omp_get_num_threads();
        maxt = omp_get_max_threads();
        inpar = omp_in_parallel();
        dynamic = omp_get_dynamic();
        nested = omp_get_nested();
```

Get Environment Information in OpenMP

```
        /* Print environment information */
        printf("Number of processors = %d\n", procs);
        printf("Number of threads = %d\n", nthreads);
        printf("Max threads = %d\n", maxt);
        printf("In parallel? = %d\n", inpar);
        printf("Dynamic threads enabled? = %d\n", dynamic);
        printf("Nested parallelism supported? = %d\n", nested);
      }
  }  /* Parallel Done */

}
```


Get Environment Information in OpenMP

```
Thread 0 getting environment info...
Number of processors = 2
Number of threads = 2
Max threads = 1
In parallel? = 1
Dynamic threads enabled? = 0
Nested parallelism supported? = 0
```

Executes two threads
Prints information from thread 0 only
At this point just one thread available, hence max threads = 1

Workshare `for loop` Example #1 in OpenMP

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#define CHUNKSIZE   10
#define N       100
int main (int argc, char *argv[])
{ int nthreads, tid, i, chunk;
  float a[N], b[N], c[N];

  /* Some initializations */
  for (i=0; i < N; i++)
     a[i] = b[i] = i * 1.0;
  chunk = CHUNKSIZE;
```


Workshare `for loop` Example #1 in OpenMP

```
#pragma omp parallel shared(a,b,c,nthreads,chunk) private(i,tid)
  { tid = omp_get_thread_num();
    if (tid == 0){
       nthreads = omp_get_num_threads();
       printf("Number of threads = %d\n", nthreads);
    }
    printf("Thread %d starting...\n",tid);

    #pragma omp for schedule(dynamic,chunk)
    for (i=0; i<N; i++){
       c[i] = a[i] + b[i];
       printf("Thread %d: c[%d]= %f\n",tid,i,c[i]);
    }
  }  /* end of parallel section */
}
```

The iterations of a loop are scheduled dynamically across the team of threads. A thread will perform CHUNK iterations at a time before being scheduled for the next CHUNK of work.

Workshare `for loop` Example #1 in OpenMP

```
Number of threads = 2
Thread 0 starting...
Thread 1 starting...
Thread 0: c[0]= 0.000000
Thread 1: c[10]= 20.000000
Thread 0: c[1]= 2.000000
Thread 1: c[11]= 22.000000
Thread 0: c[2]= 4.000000
Thread 1: c[12]= 24.000000
Thread 0: c[3]= 6.000000
Thread 1: c[13]= 26.000000
Thread 0: c[4]= 8.000000
Thread 1: c[14]= 28.000000
Thread 0: c[5]= 10.000000
Thread 1: c[15]= 30.000000
Thread 0: c[6]= 12.000000
Thread 1: c[16]= 32.000000
Thread 1: c[17]= 34.000000
Thread 1: c[18]= 36.000000
Thread 0: c[7]= 14.000000
Thread 1: c[19]= 38.000000
Thread 0: c[8]= 16.000000
Thread 1: c[20]= 40.000000
Thread 0: c[9]= 18.000000
Thread 1: c[21]= 42.000000
Thread 0: c[30]= 60.000000
Thread 1: c[22]= 44.000000
Thread 0: c[31]= 62.000000
Thread 1: c[23]= 46.000000
```

```
. . .
Thread 0: c[78]= 156.000000
Thread 1: c[25]= 50.000000
Thread 0: c[79]= 158.000000
Thread 1: c[26]= 52.000000
Thread 0: c[80]= 160.000000
Thread 1: c[27]= 54.000000
Thread 0: c[81]= 162.000000
Thread 1: c[28]= 56.000000
Thread 0: c[82]= 164.000000
Thread 1: c[29]= 58.000000
Thread 0: c[83]= 166.000000
Thread 1: c[90]= 180.000000
Thread 0: c[84]= 168.000000
Thread 1: c[91]= 182.000000
Thread 0: c[85]= 170.000000
Thread 1: c[92]= 184.000000
Thread 0: c[86]= 172.000000
Thread 1: c[93]= 186.000000
Thread 0: c[87]= 174.000000
Thread 1: c[94]= 188.000000
Thread 0: c[88]= 176.000000
Thread 1: c[95]= 190.000000
Thread 0: c[89]= 178.000000
Thread 1: c[96]= 192.000000
Thread 1: c[97]= 194.000000
Thread 1: c[98]= 196.000000
Thread 1: c[99]= 198.000000
```


Workshare `sections` Example #2 in OpenMP

```
#include <omp.h>
#include <stdio.h>
#include <stdlib.h>
#define N     50
int main (int argc, char *argv[])
{ int i, nthreads, tid;
  float a[N], b[N], c[N], d[N];

/* Some initializations */
for (i=0; i<N; i++) {
  a[i] = i * 1.5;
  b[i] = i + 22.35;
  c[i] = d[i] = 0.0;
  }
```

Workshare `sections` Example #2 in OpenMP

```
#pragma omp parallel private(i,tid)
{   tid = omp_get_thread_num();
    if (tid == 0) {
       nthreads = omp_get_num_threads();
       printf("Number of threads = %d\n", nthreads);
    }
    printf("Thread %d starting...\n",tid);
    #pragma omp sections nowait
    {    #pragma omp section
         {
            printf("Thread %d doing section 1\n",tid);
            for (i=0; i<N; i++){
               c[i] = a[i] + b[i];
               printf("Thread %d: c[%d]= %f\n",tid,i,c[i]);
         }
     }
```

Sections

Workshare `sections` Example #2 in OpenMP

```
       #pragma omp section
       {  printf("Thread %d doing section 2\n",tid);
          for (i=0; i<N; i++){
             d[i] = a[i] * b[i];
             printf("Thread %d: d[%d]= %f\n",tid,i,d[i]);
          }
       }
     }  /* end of sections */
     printf("Thread %d done.\n",tid);
    }  /* end of parallel section */
  }
}
```

Sections

Workshare `sections` Example #2 in OpenMP

```
Number of threads = 2
Thread 1 starting...
Thread 0 starting...
Thread 1 doing section 1
Thread 0 doing section 2
Thread 1: c[0]= 22.350000
Thread 0: d[0]= 0.000000
Thread 1: c[1]= 24.850000
Thread 0: d[1]= 35.025002
Thread 1: c[2]= 27.350000
Thread 0: d[2]= 73.050003
Thread 1: c[3]= 29.850000
Thread 0: d[3]= 114.075005
Thread 1: c[4]= 32.349998
Thread 0: d[4]= 158.100006
Thread 1: c[5]= 34.849998
Thread 0: d[5]= 205.125000
Thread 1: c[6]= 37.349998
Thread 0: d[6]= 255.150009
Thread 1: c[7]= 39.849998
Thread 0: d[7]= 308.175018
Thread 0: d[8]= 364.200012
Thread 0: d[9]= 423.225006
Thread 0: d[10]= 485.249969
Thread 0: d[11]= 550.274963
Thread 0: d[12]= 618.299988
Thread 0: d[13]= 689.324951
Thread 0: d[14]= 763.349976
Thread 0: d[15]= 840.374939
```

```
. . .
Thread 1: c[33]= 104.849998
Thread 0: d[41]= 3896.024902
Thread 1: c[34]= 107.349998
Thread 0: d[42]= 4054.049805
Thread 1: c[35]= 109.849998
Thread 0: d[43]= 4215.074707
Thread 1: c[36]= 112.349998
Thread 0: d[44]= 4379.100098
Thread 1: c[37]= 114.849998
Thread 1: c[38]= 117.349998
Thread 1: c[39]= 119.849998
Thread 1: c[40]= 122.349998
Thread 1: c[41]= 124.849998
Thread 1: c[42]= 127.349998
Thread 1: c[43]= 129.850006
Thread 1: c[44]= 132.350006
Thread 0: d[45]= 4546.125000
Thread 1: c[45]= 134.850006
Thread 0: d[46]= 4716.149902
Thread 1: c[46]= 137.350006
Thread 0: d[47]= 4889.174805
Thread 1: c[47]= 139.850006
Thread 0: d[48]= 5065.199707
Thread 0: d[49]= 5244.225098
Thread 0 done.
Thread 1: c[48]= 142.350006
Thread 1: c[49]= 144.850006
Thread 1 done.
```

Nowait in sections

Calculating π using Numerical Integration

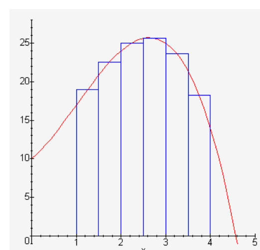
$$\pi = \int_0^1 \frac{4}{1+x^2}\,dx$$

Riemann Sum Approximation:

$$\int_a^b f(x)dx = \lim_{||P||\to 0} \sum_{i=1}^{n} f(x_i^*)\Delta x_i$$

P is a partition of [a, b] into n subintervals,
$[x_0, x_1]$, $[x_1, x_2]$, . . . , $[x_{n-1}, x_n]$ each of width x.
x_i^* is in the interval $[x_{i-1}, x_i]$ for each i.
As || P || → 0, n → infinity and x → 0.

x_i^* to be the midpoint of each subinterval,
i.e. $x_i^* = ½(x_{i-1} + x_i)$, for each i from 1 to n.



http://www.youtube.com/watch?v=H20cKjz-bjw

Sequential Calculation of π in C

```
#include <stdio.h>
/* Serial Code */
static long num_steps = 100000;
double step;
int main (int argc, char *argv[]) {
    int i; double x, pi, sum = 0.0;
    step = 1.0/(double) num_steps;
    for (i=0; i < num_steps; i++){
       x = (i+0.5)*step;
       sum = sum + 4.0/(1.0+x*x);
    }
    pi = sum/num_steps;
    printf ("pi = %6.12f\n", pi);
}
```

pi = 3.14159265

OpenMP Version #1

```
#include <omp.h>
static long num_steps = 100000; double step;
#define NUM_THREADS 2
int main (int argc, char *argv[]){
    int i, id; double  x, pi, sum[NUM_THREADS];
    step = 1.0/(double) num_steps;
    #pragma omp parallel private(x)
    {
       id = omp_get_thread_num();
       for (i = id, sum[id] = 0.0; i < num_steps;
            i = i + NUM_THREADS) {
              x = (i + 0.5)*step;
              sum[id] += 4.0/(1.0+x*x);
       }
    }
    for(i = 0, pi = 0.0; i < NUM_THREADS; i++)
       pi += sum[i] ;
    printf ("pi = %6.12f\n", pi / num_steps);
}
```

OpenMP Version #1 (with bug)

pi = 2.187926626214	pi = 3.141592653598
pi = 3.062113243183	pi = 1.999849495043
pi = 2.093066397959	pi = 2.348751552706
pi = 3.141592653598	pi = 1.858418846828
pi = 2.199725334399	pi = 3.141592653598
pi = 2.129254580053	pi = 3.141592653598
pi = 3.298710582772	pi = 2.425973292566
pi = 2.358075931672	pi = 3.141592653598
pi = 1.979735213760	pi = 2.024963879529
pi = 3.134406923694	pi = 2.357897349032
pi = 3.141592653598	pi = 2.325699828349
pi = 2.273284475646	pi = 1.825693174923

OpenMP Version #1

```
#include <omp.h>
static long num_steps = 100000; double step;
#define NUM_THREADS 2
int main (int argc, char *argv[]){
   int i, id; double  x, pi, sum[NUM_THREADS];
   step = 1.0/(double) num_steps;
   #pragma omp parallel private(x)
   {
      id = omp_get_thread_num();
      for (i = id, sum[id] = 0.0; i < num_steps;
         i = i + NUM_THREADS) {
            x = (i + 0.5)*step;
            sum[id] += 4.0/(1.0+x*x);
      }
   }
   for(i = 0, pi = 0.0; i < NUM_THREADS; i++)
      pi += sum[i] ;
   printf ("pi = %6.12f\n", pi / num_steps);
}
```


OpenMP Critical Section

```
#include <omp.h>
int main(void)
{
   int x;
   x = 0;
   #pragma omp parallel
   {
      #pragma omp critical
      x = x + 1;
   }  /* end of parallel section */
}
```

Only one thread executes the following code block at a time

Compiler generates necessary lock/unlock code around the increment of x

Student Roulette?

OpenMP Version #2

```
#include <omp.h>
static long num_steps = 100000; double step;
#define NUM_THREADS 2
int main (int argc, char *argv[]) {
   int i, id; double  x, sum, pi=0.0;
   step = 1.0/(double) num_steps;
   #pragma omp parallel private (x, sum) {
      id = omp_get_thread_num();
      for (i = id, sum = 0.0; i < num_steps;
         i = i + NUM_THREADS){
            x = (i + 0.5)*step;
            sum += 4.0/(1.0+x*x);
      }
      #pragma omp critical
      pi += sum;
   }
   printf ("pi = %6.12f,\n", pi/num_steps);
}
```


OpenMP Version #2 (with bug)

pi = 2.193065170635	pi = 3.141592653598
pi = 2.094493774172	pi = 2.446564596856
pi = 2.941181318377	pi = 2.292319872127
pi = 3.706889160821	pi = 3.430000515865
pi = 3.146809442180	pi = 3.650290478614
pi = 2.416534126971	pi = 1.988308636488
pi = 3.141592653598	pi = 3.141592653598
pi = 2.880126390443	pi = 2.516381208613
pi = 2.012071161080	pi = 3.141592653598
pi = 2.294675684941	pi = 2.331351828709
pi = 2.769967988388	pi = 2.245872892167
pi = 2.373218039482	pi = 1.928775146184

OpenMP Reduction

- *Reduction*: specifies that one or more variables that are private to each thread are subject of reduction operation at end of parallel region:
  `reduction(operation:var)` where
  - *Operation*: operator to perform on the variables (var) at the end of the parallel region
  - *Var*: One or more variables on which to perform scalar reduction

```
#pragma omp for reduction(+:nSum)
  for (i = START ; i <= END ; i++)
     nSum += i;
```

OpenMP Version #3

Note: Don't have to declare for loop index variable **i** private, since that is default

```
#include <omp.h>
#include <stdio.h>
/static long num_steps = 100000;
double step;
int main (int argc, char *argv[]){
    int i; double x, pi, sum = 0.0;
    step = 1.0/(double) num_steps;
    #pragma omp parallel for private(x) reduction(+:sum)
       for (i = 0; i < num_steps; i++){
          x = (i+0.5)*step;
          sum = sum + 4.0/(1.0+x*x);
       }
    pi = sum / num_steps;
    printf ("pi = %6.8f\n", pi);
}
```


OpenMP Timing

- omp_get_wtime – Elapsed wall clock time

```
double omp_get_wtime(void);
#include <omp.h> // to get function
```

- Elapsed wall clock time in seconds. Time is measured per thread, no guarantee can be made that two distinct threads measure the same time. Time is measured from some "time in the past". On POSIX compliant systems the seconds since the Epoch (00:00:00 UTC, January 1, 1970) are returned.

OpenMP Version #3

pi = 3.14159265 in 0.176 seconds	pi = 3.14159265 in 0.177 seconds
pi = 3.14159265 in 0.190 seconds	pi = 3.14159265 in 0.178 seconds
pi = 3.14159265 in 0.178 seconds	pi = 3.14159265 in 0.182 seconds
pi = 3.14159265 in 0.177 seconds	pi = 3.14159265 in 0.181 seconds
pi = 3.14159265 in 0.182 seconds	pi = 3.14159265 in 0.176 seconds
pi = 3.14159265 in 0.181 seconds	pi = 3.14159265 in 0.181 seconds
pi = 3.14159265 in 0.177 seconds	pi = 3.14159265 in 0.184 seconds
pi = 3.14159265 in 0.178 seconds	pi = 3.14159265 in 0.177 seconds
pi = 3.14159265 in 0.177 seconds	pi = 3.14159265 in 0.178 seconds
pi = 3.14159265 in 0.179 seconds	pi = 3.14159265 in 0.178 seconds
pi = 3.14159265 in 0.180 seconds	pi = 3.14159265 in 0.183 seconds
pi = 3.14159265 in 0.190 seconds	pi = 3.14159265 in 0.180 seconds

Agenda

- OpenMP Introduction
- Administrivia
- OpenMP Examples
- **Break**
- Common Pitfalls
- Summary

OpenMP Version #4

```
#include <omp.h>
static long num_steps = 100000; double step;
int main (int argc, char *argv[]){
   int i, id; double  x, pi, sum;
   sum = 0.0;
   step = 1.0/(double) num_steps;
   #pragma omp parallel
   {
      #pragma omp for
         for (i = 0; i < num_steps; i++) {
            x = (i + 0.5)*step;
            sum += 4.0/(1.0+x*x);
         }
   }
   printf ("pi = %6.12f\n", step * sum);
}
```


OpenMP Version #4 (with bug)

pi = 1.265327037088	pi = 1.193981730178
pi = 1.961754300795	pi = 1.311730912439
pi = 1.702630397118	pi = 3.141592653598
pi = 3.113547769550	pi = 1.555278403355
pi = 2.491334675594	pi = 2.135597106908
pi = 1.476785567928	pi = 1.800509862440
pi = 1.307626664756	pi = 1.182105369813
pi = 1.303385815200	pi = 3.141592653598
pi = 3.141592653598	pi = 1.944801017796
pi = 3.141592653598	pi = 1.227297673420
pi = 1.155505463020	pi = 2.487932948250
pi = 1.514950670570	pi = 1.875190752727

OpenMP Version #5

```
#include <omp.h>
static long num_steps = 100000; double step;
int main (int argc, char *argv[]){
   int i, id; double x, pi, sum, sum0;
   sum = 0.0;
   step = 1.0/(double) num_steps;
#pragma omp parallel private(x,sum0) shared
  (step,sum)
   {
     sum0 = 0.0;
     #pragma omp for
        for (i = 0; i < num_steps; i++) {
           x = (i + 0.5)*step;
           sum0 += 4.0/(1.0+x*x);
        }
     sum = sum + sum0;
   }
   printf ("pi = %6.12f\n", step * sum);
}
```


OpenMP Version #6

```
#include <omp.h>
static long num_steps = 100000; double step;
int main (int argc, char *argv[]){
   int i, id; double x, pi, sum, sum0;
   sum = 0.0;
   step = 1.0/(double) num_steps;
#pragma omp parallel private(x,sum0) shared
  (step,sum)
   {
     sum0 = 0.0;
     #pragma omp for
        for (i = 0; i < num_steps; i++) {
           x = (i + 0.5)*step;
           sum0 += 4.0/(1.0+x*x);
        }
     #pragma omp critical
        {
           sum = sum + sum0;
        }
   }
   printf ("pi = %6.12f\n", step * sum);
}
```


OpenMP Version #6

pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598
pi = 3.141592653598	pi = 3.141592653598

Matrix Multiply in OpenMP

```
start_time = omp_get_wtime();
#pragma omp parallel for private(tmp, i, j, k)
  for (i=0; i<Ndim; i++){
     for (j=0; j<Mdim; j++){
        tmp = 0.0;
        for( k=0; k<Pdim; k++){
           /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
           tmp += *(A+(i*Ndim+k)) * *(B+(k*Pdim+j));
        }
      *(C+(i*Ndim+j)) = tmp;
     }
  }
run_time = omp_get_wtime() - start_time;
```

Note: Outer loop spread across N threads; inner loops inside a thread

Notes on Matrix Multiply Example

More performance optimizations available

- Higher compiler optimization (-O2, -O3) to reduce number of instructions executed
- Cache blocking to improve memory performance
- Using SIMD SSE3 Instructions to raise floating point computation rate

OpenMP Pitfall #1: Data Dependencies

- Consider the following code:

```
a[0] = 1;
for(i=1; i<5; i++)
a[i] = i + a[i-1];
```

- There are dependencies between loop iterations
- Sections of loops split between threads will not necessarily execute in order
- Out of order loop execution will result in undefined behavior

Open MP Pitfall #2: Avoiding Sharing Issues by Using Private Variables

- Consider the following loop:

```
#pragma omp parallel for
{
        for(i=0; i<n; i++){
            temp = 2.0*a[i];
            a[i] = temp;
            b[i] = c[i]/temp;
        }
}
```

- Threads share common address space: will be modifying temp simultaneously; solution:

```
#pragma omp parallel for private(temp)
{
    for(i=0; i<n; i++){
        temp = 2.0*a[i];
        a[i] = temp;
        b[i] = c[i]/temp;
    }
}
```


OpenMP Pitfall #3: Updating Shared Variables Simultaneously

- Now consider a global sum:

```
for(i=0; i<n; i++)
     sum = sum + a[i];
```

- This can be done by surrounding the summation by a critical section, but for convenience, OpenMP also provides the reduction clause:

```
#pragma omp parallel for reduction(+:sum)
{
     for(i=0; i<n; i++)
          sum = sum + a[i];
}
```

- Compiler can generate highly efficient code for reduction

OpenMP Pitfall #4: Parallel Overhead

- Spawning and releasing threads results in significant overhead
- Therefore, you want to make your parallel regions as large as possible
  - Parallelize over the largest loop that you can (even though it will involve more work to declare all of the private variables and eliminate dependencies)
  - Coarse granularity is your friend!

OpenMP Pitfall #4: Parallel Overhead

```
start_time = omp_get_wtime();
  for (i=0; i<Ndim; i++){
     for (j=0; j<Mdim; j++){
        tmp = 0.0;
        #pragma omp parallel for reduction(+:tmp)
        for( k=0; k<Pdim; k++){
           /* C(i,j) = sum(over k) A(i,k) * B(k,j)*/
           tmp += *(A+(i*Ndim+k)) * *(B+(k*Pdim+j));
        }
      *(C+(i*Ndim+j)) = tmp;
     }
  }
run_time = omp_get_wtime() - start_time;
```

Way too much overhead in thread generation to have this statement run this frequently

And in Conclusion, …

- Synchronization via atomic operations:
  - MIPS does it with Load Linked + Store Conditional
- OpenMP as simple parallel extension to C
  - Threads, Parallel for, private, critical sections, …