PROGRAMMING WITH SHARED MEMORY

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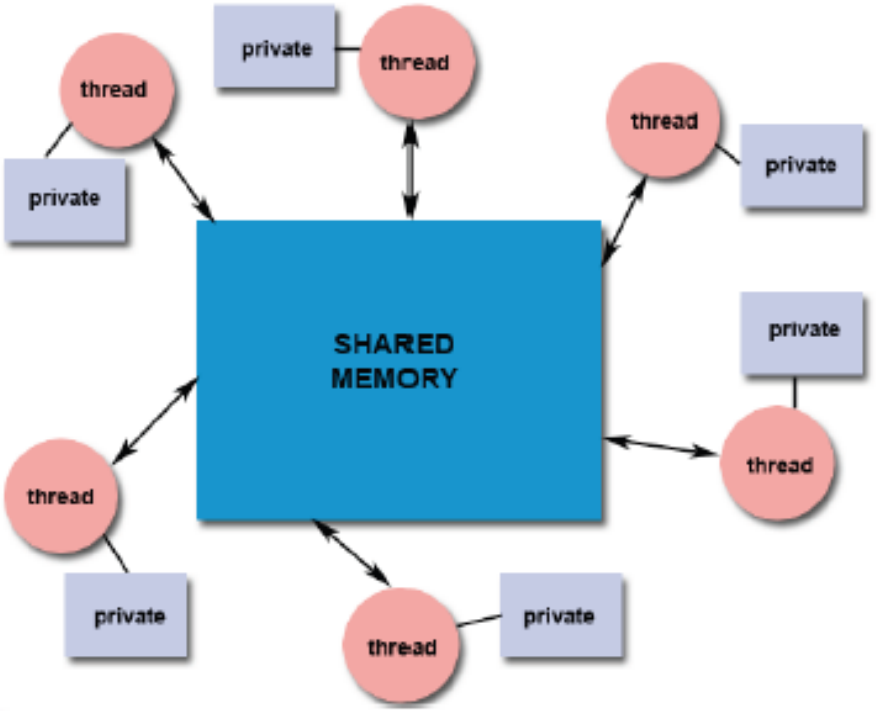
Aug 23, 2012

How to program machines?

- Distributed - Memory Machines
  - Each node in the computer has a locally addressable memory space
  - Parallel programs consists of cooperating processes, each with its own memory
  - Processes send data to one another as messages. **Message Passing Interface (MPI)** is a widely used standard for writing message-passing programs
- Shared - Memory Machines
  - Each core can access the entire data space
  - In shared memory multi-core architectures, **OpenMP, Pthreads** can be used to implement parallelism

Shared Memory Model



- All threads have access to the same, **global shared,** memory.
- Threads also have their own private memory.
- Shared data is accessible by all threads.
- Private data can be only accessed by the thread that owns it.
- Programmers are responsible for synchronizing access (protecting) globally shared data.

Labeling the data

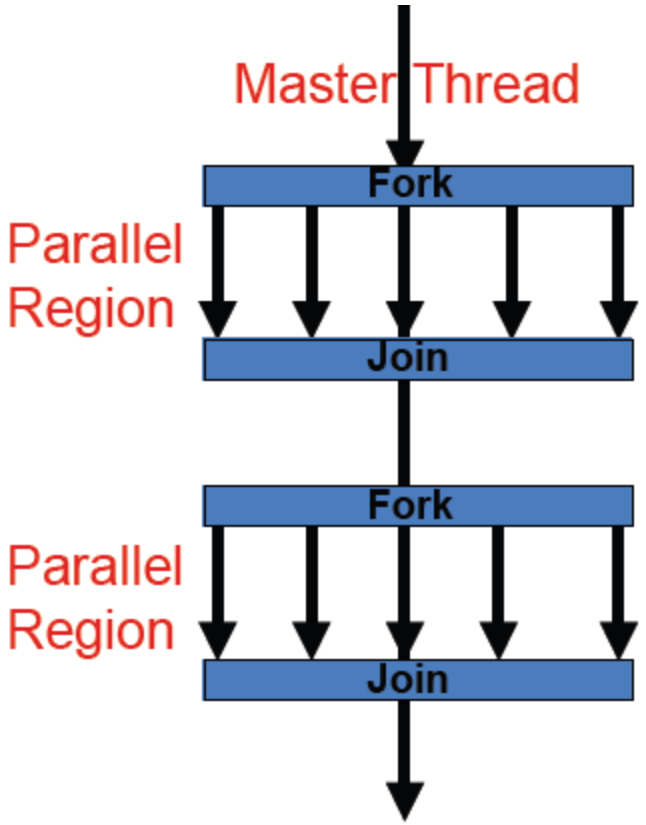
As programmers we need to think about where in the memory we can put the data

- **Shared**
  - All threads can read and write the data simultaneously.
  - The changes are visible to all threads.
- **Private**
  - Thread has a copy of the data.
  - Other thread can not access to this data.
  - The changes are visible to only the thread that owns the data.

Common model for threaded program

Fork-Join Model

- Master threads runs from start to end.
- When the parallelism is specified, the main thread gets help from the threads that are called worker threads.
- At the end of the parallel portion of the work, the threads synchronize and terminate.
- Only the main thread leaves



Start with auto parallelization

- IBM XL thread safe compilers will automatically parallelize your code if
  - There is no branching into or out of the loop.
  - The increment expression is not within a critical section.
  - The order in which loop iterations start and end doesn't affect the result.
  - The loop doesn't contain I/O operations
  - The program is compiled with a thread-safe version of compiler. (_r suffix : mpixlc_r, mpixlcxx_r, mpixlf77_r,…)

Shared Memory Programming Pthreads

POSIX threads (Portable Operating System Interface) threads

Shared Memory Programming: Pthreads

- Hardware vendors have their own versions of threads. Difficult for programmers to develop portable threaded applications.

- For UNIX systems, a standardized programming interface specified by the IEEE POSIX 1003.1c standard. This standard are referred to as POSIX threads.

POSIX Threads - Pthreads

- Pthreads API contains around 100 subroutine
- pthread.h header file should be included
- POSIX standard for the C language. Fortran programmers can use wrappers around C function calls. *IBM XL provides a Fortran pthreads API.*

Routine Prefix	Functional Group
pthread_	Threads themselves and miscellaneous subroutines
pthread_attr_	Thread attributes objects
pthread_mutex_	Mutexes
pthread_mutexattr_	Mutex attributes objects.
pthread_cond_	Condition variables
pthread_condattr_	Condition attributes objects
pthread_key_	Thread-specific data keys
pthread_rwlock_	Read/write locks
pthread_barrier_	Synchronization barriers

Compiling Threaded Programs

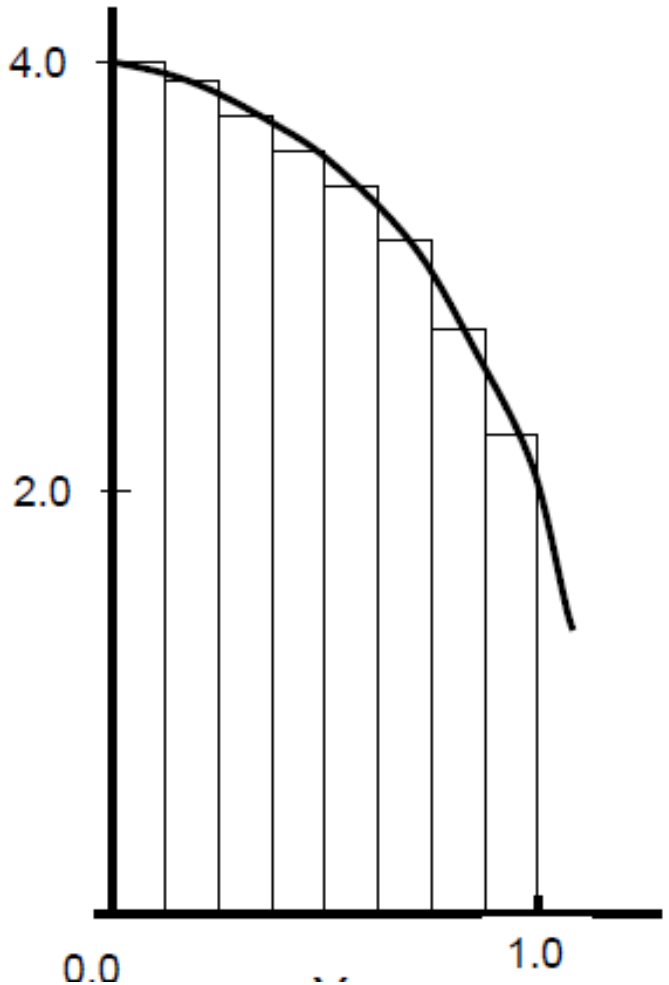
Compiler / Platform	Compiler Command
INTEL Linux	**icc -pthread**
	icpc -pthread
PGI Linux	**pgcc -lpthread**
	pgCC -lpthread
GNU Linux, Blue Gene	**gcc -pthread**
	g++ -pthread
IBM Blue Gene	**bgxlc_r / bgcc_r**
	bgxlC_r, bgxlc++_r

IBM Blue Gene P: If you want to use fewer than the number of available you need to set in your LoadLeveler batch job file

@ arguments = **-env XLSMPOPTS=PARTHDS=2** -exe …

Example: PI

3.14159265358979323846264338327950288419716



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

NUMERICAL INTEGRATION

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

Serial Code in C

```
#include <stdio.h>
#define NUMSTEPS 1000000

int main ()
{
        int i;
        double x, Pi, step, sum = 0.0;

        step = 1.0/NUMSTEPS;

        for(i = 0; i <= NUMSTEPS; ++i)
        {
                x = (i+0.5)*step;
                sum += 4.0 / (1.0+x*x);
        }
        Pi = step * sum;

        return 0;
}
```

Creating and Terminating Threads

- Creating Threads:
  - A single, default thread in your main() program
  - Other threads must be explicitly created by the programmer.

pthread_create(thread, attr, start_routine, arg)

.

identifier for the new thread returned by the subroutine

attribute object used to set thread attributes

C routine that the thread execute once it is created

argument that is passed to start_routine

- Terminating Threads: **pthread_exit()**

```
#include <stdio.h>
#include <pthread.h>
#define NUMSTEPS 1000000
#define NUMTHRDS 4

double step = 0.0, Pi = 0.0;
pthread_mutex_t mutexsum;

void *Pi_Func(void *pArg)
{
        int    i, myrank = *((int *)pArg);
        double x, mysum = 0.0;

        for (i = myrank; i < NUMSTEPS; i += NUMTHRDS)
        {
                x = (i + 0.5) * step;
                mysum += 4.0 / (1.0 + x*x);
        }

        pthread_mutex_lock(&mutexsum);
                printf("Thread %ld adding partial sum %f.\n",pArg, mysum);
                Pi += mysum * step;
        pthread_mutex_unlock(&mutexsum);

        return 0;
}
```

Define globally accessible variables and a mutex

Lock a mutex prior to updating the value in the shared structure

unlock it upon updating

```
int main ()
{
        pthread_t  callThd[NUMTHRDS];
        int     i;
        step = 1.0/ NUMSTEPS;

        pthread_mutex_init(&mutexsum, NULL);

        for(i=0; i<NUMTHRDS; i++) {
          pthread_create( &callThd[i], NULL, Pi_Func, (void *)i);
        }

        for(i=0; i<NUMTHRDS; i++) {
                pthread_join( callThd[i], NULL);
        }

        printf ("Threaded version: Pi =  %f \n", Pi);

        pthread_mutex_destroy(&mutexsum);
        pthread_exit(NULL);
}
```

Create threads

Wait on the other threads

After joining, print out the results and cleanup

Shared Memory Programming OpenMP

OpenMP
Open Multi-Processing

Shared Memory Programming: OpenMP

OpenMP = Open Multi-Processing

- The OpenMP Application Program Interface (API) for writing shared memory parallel programs.
- Supports multi-platform shared-memory parallel programming in C/C++ and Fortran on all architectures.
- Consists of
  - Compiler Directives
  - Runtime Library Routines
  - Environment Variables
- OpenMP program is portable. Compilers have OpenMP support.
- Requires little programming effort.

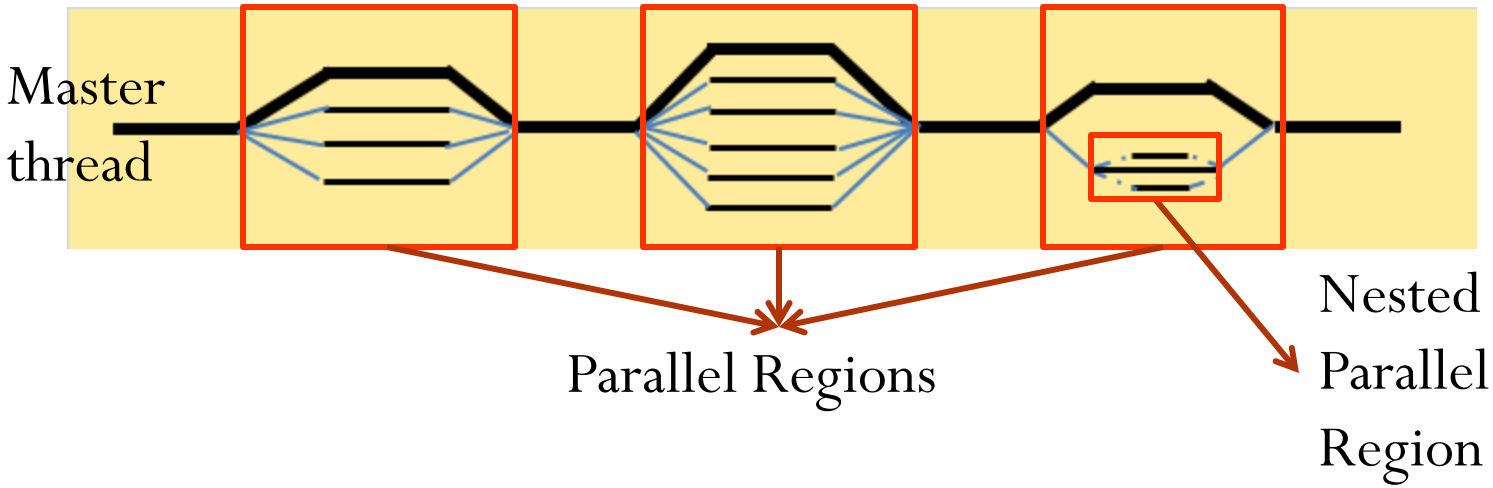
Compiling Threaded Programs

Compiler / Platform	Compiler	Flag
Intel Linux Opteron/Xeon	icc icpc ifort	-openmp
PGI Linux Opteron/Xeon	pgcc pgCC pgf77 pgf90	-mp
GNU Linux Opteron/Xeon IBM Blue Gene	gcc g++ g77 gfortran	-fopenmp
IBM Blue Gene	bgxlc_r, bgcc_r bgxlC_r, bgxlc++_r bgxlc89_r bgxlc99_r bgxlf_r bgxlf90_r bgxlf95_r bgxlf2003_r	-qsmp=omp

IBM Blue Gene P: If you want to use fewer than the number of available you need to set in your LoadLeveler batch job file

@ arguments = **-env OMP_NUM_THREADS=2 -exe …**

OpenMP Execution Model



OpenMP uses the fork-join model

FORK: the master thread creates a team of parallel threads

Labeling the data

- Most variables are shared by default
- Global variables: File scope variables, static
- Private variables:
  - Do/For Loop index variables
  - Stack variables in functions called from parallel regions

The OpenMP API
three distinct components

As of version 3.1

- Compiler Directives (20)
- Runtime Library Routines (32)
- Environment Variables (9)

Compiler Directives

- In source code **compiler directives** are used for
  - Spawning a parallel region
  - Dividing blocks of code among threads
  - Distributing loop iterations between threads
  - Serializing sections of code
  - Synchronization of work among threads

sentinel ***directive-name*** ***[clause, …]***

Fortran	!$OMP PARALLEL DEFAULT(SHARED) PRIVATE(…)
C/C++	#pragma omp parallel default(shared) private(…)

Runtime Library Routines

- Include the <omp.h> header file
- These routines are used for:
  - Setting and querying
    - the number of threads
    - the dynamic threads feature
    - nested parallelism
    - thread's unique identifier (thread ID), the thread team size
    - wall clock time and resolution
  - initializing and terminating locks and nested locks
- Fortran routines are not case sensitive, C/C++ routines are

Fortran	INTEGER FUNCTION OMP_GET_NUM_THREADS()
C/C++	int omp_get_num_threads(void)

Environment Variables

- control the execution of parallel code at run-time
- Set the same way set any other environment variables

OMP_SCHEDULE	how iterations of the loop are scheduled on processors
OMP_NUM_THREADS	Sets the maximum number of threads
OMP_DYNAMIC	Enables or disables dynamic adjustment of the threads
OMP_PROC_BIND	Enables or disables threads binding to processors
OMP_NESTED	Enables or disables nested parallelism
OMP_STACKSIZE	Controls the size of the stack for non-Master threads
OMP_WAIT_POLICY	ACTIVE /PASSIVE
OMP_MAX_ACTIVE_LEVELS	Controls the maximum number of nested active parallel regions
OMP_THREAD_LIMIT	Sets the number of threads to use for the whole program

Parallel Regions: Thread creation

```
omp_set_num_threads(4);
#pragma omp parallel
{
  int tid = omp_get_thread_num();
  ...
}
```

Sets the number of threads that will be used in the next parallel region

Returns the thread number of the thread, within the team

```
#pragma omp parallel num_threads(4)
{
  int tid = omp_get_thread_num();
  ...
}
```

Clause to request a number of threads

Each thread executes the section of the code in parallel region

```
#include <stdio.h>
#include <omp.h>
#define NUMSTEPS 1000000
#define NUMTHRDS 4

int main ()
{
        int i, nthreads;
        double step, sum[NUMTHRDS], Pi=0.0;
        step = 1.0/NUMSTEPS;

        omp_set_num_threads(NUMTHRDS);

#pragma omp parallel
{
        int tid, nthrds;
        double x;
        tid = omp_get_thread_num();
        nthrds = omp_get_num_threads();
        if ( tid == 0 )
                nthreads = omp_get_num_threads();
        for(i = tid, sum[tid]=0; i <= NUMSTEPS; i+=nthrds)
        {
                x = (i+0.5)*step;
                sum[tid] += 4.0 / (1.0+x*x);
        }
}
        for (i=0; i<nthreads; i++)
                Pi += step * sum[i];

        return 0;
}
```

POOR SCALING

False sharing occurs when processors in a shared-memory parallel system make references to different data objects within the same coherence block (cache line or page), thereby inducing "unnecessary" coherence operations.

Bolosky, W. J. and Scott, M. L. 1993. *False sharing and its effect on shared memory performance*

```
#include <stdio.h>
#include <omp.h>
#define NUMSTEPS 1000000
#define NUMTHRDS 4

int main ()
{
        int i, nthreads;
        double step, Pi=0.0;
        step = 1.0/NUMSTEPS;

        omp_set_num_threads(NUMTHRDS);

#pragma omp parallel
{
        int tid, nthrds;
        double x, sum;
        tid = omp_get_thread_num();
        nthrds = omp_get_num_threads();
        if ( tid == 0 )
                nthreads = omp_get_num_threads();
        for(i = tid, sum=0.0; i <= NUMSTEPS; i+=nthrds)
        {
                x = (i+0.5)*step;
                sum += 4.0 / (1.0+x*x);
        }
        #pragma omp critical
                Pi += step * sum;
}

        return 0;
}
```

CRITICAL directive
executed by only one thread at a time

Work-Sharing Constructs
DO / for Directive

Fortran	!$OMP DO *[clause …]* *do_loop* !$OMP END DO [NOWAIT]
C/C++	#pragma omp for *[clause …]* *for_loop*

clause

IF

PRIVATE

SHARED

DEFAULT

FIRSTPRIVATE

LASTPRIVATE

REDUCTION

COPYIN

COPYPRIVATE

SCHEDULE

ORDERED

NOWAIT

```
#include <stdio.h>
#include <omp.h>
#define NUMSTEPS 1000000
#define NUMTHRDS 4

int main ()
{
        int i, nthreads;
        double x, step, Pi=0.0, sum=0.0;
        step = 1.0/NUMSTEPS;

        omp_set_num_threads(NUMTHRDS);

#pragma omp parallel for        \
        default(shared)         \
        private(i,x)            \
        reduction(+:sum)
        for(i = 0; i <= NUMSTEPS; ++i)
        {
                x = (i+0.5)*step;
                sum += 4.0 / (1.0+x*x);
        }

        Pi += step * sum;
        return 0;
}
```

reduction *(operator: list)*

Work-Sharing Constructs SECTIONS Directive

- Barrier at the end of a SECTIONS directive
- Use NOWAIT clause to turn of the barrier
- Each SECTION within a SECTIONS directive is executed once by a thread in the team.

Fortran	**C/C++**

!$OMP SECTIONS *[clause …]*
!$OMP SECTION *block*
!$OMP SECTION *block*
!$OMP END SECTIONS [NOWAIT]
	#pragma omp sections *[clause …]*
	{
	#pragma omp section *newline*
	structured_block
	#pragma omp section *newline*
	structured_block
	}

Work-Sharing Constructs
SINGLE Directive

- the code is to be executed by only one thread in the team.
- useful when the part of the code is not thread safe (I/O)

Fortran	**C/C++**
!$OMP SINGLE *[clause …]* *block* !$OMP END SINGLE [NOWAIT]	#pragma omp single *[clause …]* *structured_block*

Data-sharing Attribute Clauses

```
#include <stdio.h>
#include <omp.h>
#define NUMSTEPS 1000000
#define NUMTHRDS 4

int main ()
{
        int i, nthreads;
        double x, step, Pi=0.0, sum=0.0;
        step = 1.0/NUMSTEPS;

        omp_set_num_threads(NUMTHRDS);

#pragma omp parallel for        \
        default(shared)         \
        private(i,x,sum)
        for(i = 0; i <= NUMSTEPS; ++i)
        {
                x = (i+0.5)*step;
                sum += 4.0 / (1.0+x*x);
        }
printf("sum = %f\n",sum);

        return 0;
}
```

Private copies of sum is not initialized

sum = 0

```
#include <stdio.h>
#include <omp.h>
#define NUMSTEPS 1000000
#define NUMTHRDS 4

int main ()
{
        int i, nthreads, tid;
        double x, step, Pi=0.0, sum=0.0;
        step = 1.0/NUMSTEPS;

        omp_set_num_threads(NUMTHRDS);

#pragma omp parallel            \
        default(shared)         \
        private(i,x,tid)        \
        firstprivate(sum)
{
        tid = omp_get_thread_num();
#pragma omp for
        for(i = 0; i <= NUMSTEPS; ++i)
        {
                x = (i+0.5)*step;
                sum += 4.0 / (1.0+x*x);
        }
        printf("Thread =%d sum=%f\n",tid,sum);
}
printf("sum = %f\n",sum);

        return 0;
}
```

Firstprivate: variables are automatically initialized from the shared variables

Comparison

PTHREADS

- To make use of Pthreads, developers must write their code specifically for this API.

```
void start_routine (void *pArg)
{
        Routines ();
}

pthread_t          tid[4];
for (int i = 1; i < 4; ++i)
pthread_create(&tid[i],NULL,start_routine, (void *)i);

start_routine();

for (int i = 1; i < 4; ++i)
        pthread_join (tid[i]);
```

OpenMP

- Easy to implement

```
omp_set_num_threads(4);
#pragma omp parallel
{
        Routines();
}
```

References

http://www.openmp.org

An Overview of OpenMP Video, Ruud van der Pas

Parallel Programming in OpenMP by Rohit Chandra, Leo Dagum, Dave Kohr, Dror Maydan, Jeff McDonald, Ramesh Menon

POSIX Threads Programming

Blaise Barney, Lawrence Livermore National Laboratory
https://computing.llnl.gov/tutorials/pthreads/

OpenMP

Blaise Barney, Lawrence Livermore National Laboratory
https://computing.llnl.gov/tutorials/openMP/