OpenMP

https://github.com/t-brown/RMACC_2016/

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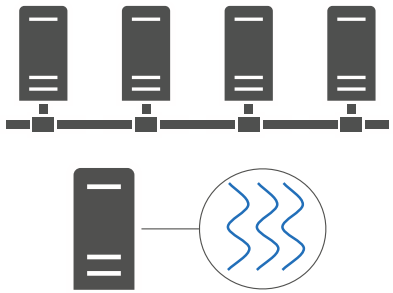
Overview

- Background
- OpenMP
- Compiler Directives
- Parallel Control
- Data Scope
- Work Sharing
- Synchronization
- Vectorization
- Accelerators

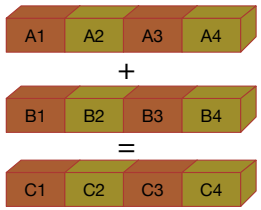
Parallelism

Parallelism can be achieved across many levels

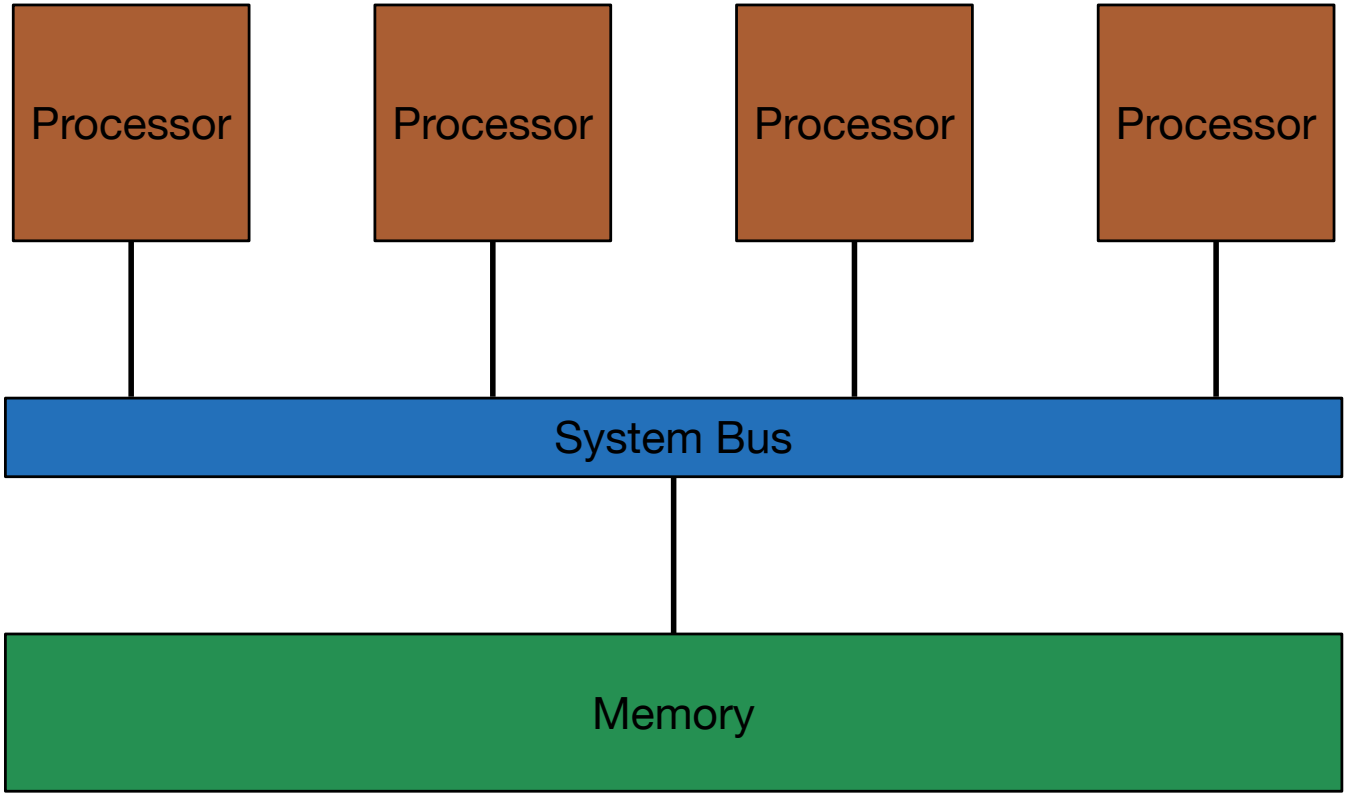
Nodes	MPI
Threads	OpenMP
Instructions	ILP
Data	SIMD



I1: add R1, R2, R3
I2: sub R4, R1, R5
I3: xor R10, R2, R11



Shared Memory Model



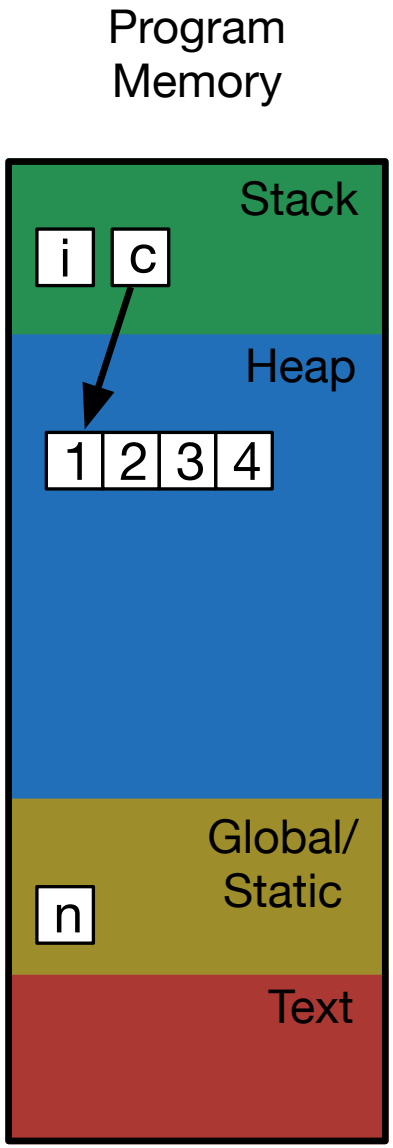
- All processors see a single view of data.
- Processors interact and synchronize through shared variables.

Memory Model

- Contents of memory segments:
  - static variables
  - variables on the run-time stack
  - functions on the run-time stack
  - dynamically allocated data on the heap

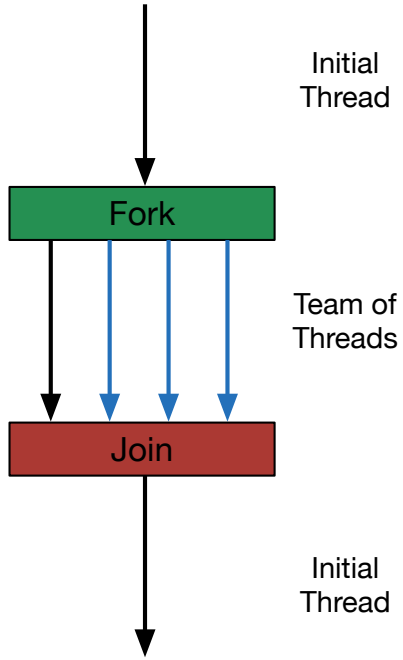
```
#include <stdlib.h>
static const int n = 4;
int
main(int argc, char **argv)
{
        int i = 0;
        int *c = NULL;

        c = malloc(n * sizeof(int));
        for (i = 0; i < n; ++i) {
                c[i] = i +1;
        }
        free(c);
        return(0);
}
```



Fork/Join Parallelism

- Program starts as a single thread of execution, initial thread.
- A team of threads is forked at the beginning of a parallel region.
- At the end of a parallel region the threads join (either die or are suspended).



OpenMP

- The OpenMP application programming interface (API) supports multi-platform shared-memory parallel programming in
  - C/C++
  - Fortran
- The API defines a portable, scalable model with a simple and flexible interface for developing parallel applications on platforms from the desktop to the supercomputer.

`http://openmp.org`

Philosophy

- Goal: Add parallelism to a functioning serial code.
- Requires: Shared memory machine.
- How: Add *compiler directives* to parallelize parts of code.
- Pro: Often very easy to add to existing code.
- Con: Large shared memory machines are expensive.

Resources

- *Using OpenMP* the book

  `https://mitpress.mit.edu/index.php?q=books/using-openmp`
- API Qucik Reference
  - C/C++
  - Fortran
- OpenMP v4.5 full API

  `http://www.openmp.org/mp-documents/openmp-4.5.pdf`
- OpenMP Examples

  `http://openmp.org/mp-documents/openmp-examples-4.0.2.pdf`

Compiler Directives

Parallel Control	Data	Work Sharing	Synchronization
Controls the flow of parallel regions	Specifies variables scope	Distribution of work between threads	Coordination of threads
parallel	shared private	for do	critical atomic barrier

Scheduling	Vectorization	Accelerators
Loop iteration distribution	Loop vectorization	Offload to co-processors GPUs
schedule	simd	target

Parallel Regions

- We tell OpenMP compiler to parallelize code.
- Mark parallel blocks.
- The compiler will spawn threads and split the work up.
- We can tell the compiler the number of threads too.

C

```c
#pragma omp parallel
{
        ...
}
```

Fortran

```fortran
!$OMP parallel
        ...
!$OMP end parallel
```

- OpenMP also provides library calls.
  - C function prototypes are in `omp.h`.
  - Fortran module interface is in `omp_lib`.
- For compatibility, you should `#ifdef` guard these calls.
- Remember to use the pre-processor for Fortran too (`.F90`).

C

```c
#ifdef _OPENMP
#include <omp.h>
#endif
```

Fortran

```fortran
#ifdef _OPENMP
  use omp_lib
#endif
```

nthreads/nthreads_c.c

```c
#include <stdlib.h>
#include <stdio.h>
#include <omp.h>

int
main(int argc, char **argv)
{

#pragma omp parallel
{
        printf("Hello world! From thread %d\n",
                omp_get_thread_num());
} /* End omp parallel */

        return(EXIT_SUCCESS);
}
```

- There is also a Fortran version `nthreads/nthreads_f.f90`.

- Compiling the program.

  GCC `gcc -fopenmp -o thread_num_c thread_num_c.c`

  Intel `icc -qopenmp -o thread_num_c thread_num_c.c`

  IBM `xlc -qsmp=omp -o thread_num_c thread_num_c.c`

- Execute the program, specifying different numbers of threads.
  1. `./thread_num_c`
  2. `env OMP_NUM_THREADS=1 ./thread_num_c`
  3. `env OMP_NUM_THREADS=64 ./thread_num_c`

- What is the output?
  - Threads printed out their identification number.
  - Random order of numbers. Threads execute independently and in general order will be random.

Variables

- We must tell the compiler how to use variables.
  - A `shared` variable has the same address in memory in every thread.
  - A `private` variable has a different address in memory in every thread.
  - A `firstprivate` is private, however it is pre-initialized.

Clauses specifies the scope of variables.

C

```
#pragma omp parallel          \
            default(none)     \
            shared(x)         \
            private(i,j)      \
```

Fortran

```
!$OMP parallel          &
!$OMP default(none)     &
!$OMP shared(x)         &
!$OMP private(i,j)
                ...
!$OMP end parallel
```

- The default is shared.
- Try and always specify `default(none)`, so as not to confuse a variables behavior. Then explicitly define every variable.
- In C, you are able to declare variables within structured blocks to reduce it's scope. This will make it a private variable. For example, `i` is shared while `j` is private.

C

```c
int i = 0;
#pragma omp parallel      \
            default(none) \
            shared(i)
{
        int j = 0;
}
```

Work Sharing

There are four work sharing constructs

- Loop Distribute iterations over the threads.
- Sections Distribute independent work units.
- Single Only one thread executes the block of code.
- Workshare Parallelize array syntax (Fortran only)

Loops

Distribute iterations over the threads.

- Makes it easy to indicate when the iterations of a loop may be executed in parallel.
- Each loop iteration must be independent of other iterations.
- Implied barrier at the end of the loop.

C

```c
#pragma omp for
for (i=0; i<10; ++i) {
    a[i] = b[i] + c[i];
}
```

Fortran

```fortran
!$OMP do
do i=1,10
    a(i) = b(i) + c(i)
end do
```

Loop Variable Clauses

- `firstprivate` pre-initialized, private variable.
- `lastprivate` last value is accessible.
- `reduction` operator is applied to the shared variable.

First Private

- Used to create private variables having initial values identical to the variable controlled by the master thread as the loop is entered.
- Variables are initialized once per thread, not once per loop iteration.
- If a thread modifies a variable's value in an iteration, subsequent iterations will get the modified value.

C

```
i = 10;
#pragma omp parallel      \
            default(none) \
            firstprivate(i)
{
    int id = omp_get_thread_num();
    i += id;
}
```

Last Private

- Sequentially last iteration: iteration that occurs last when the loop is executed sequentially.
- Used to copy back to the master thread's copy of a variable the private copy of the variable from the thread that executed the sequentially last iteration.

C

```
#pragma omp parallel for  \
            default(none) \
            shared(n)     \
            private(i)    \
            lastprivate(a)
    for(i=0; i < n; ++i) {
        a = i +1;
    }
    printf("Final value of a: %d\n", a);
```

Reduction

- Reductions are so common that OpenMP provides support for them.
- Specify reduction operation and reduction variable.
- OpenMP takes care of storing partial results in private variables and combining partial results after the loop.

C

```
#pragma omp parallel for  \
            default(none) \
            shared(x, n)  \
            private(i)    \
            reduction(+:t)
    for(i=0; i < n; ++i) {
        t += x[i];
    }
```

Exercise

- **Perform an array addition.**
- Use a sufficiently large array (eg. 10^7).
- Define the default data scope to be `none`.
- Time the serial vs OpenMP versions.

Synchronization

Synchronization helps to organize access to shared data by multiple threads.

- High level:
  - atomic
  - critical
  - barrier
  - ordered
- Low level:
  - locks
  - flush

Barrier

- Synchronizes all threads in team.
- When a `barrier` directive is reached, a thread will wait at that point until all other threads have reached that barrier.
- All threads resume executing in parallel the code that follows the barrier.

C

```c
#pragma omp parallel       \
            default(none)  \
            shared(x, t)   \
            private(i)     \
            firstprivate(n)
{
    int id = omp_get_thread_num();
    x[id] = id;
    sleep(id);
    #pragma omp barrier
    #pragma omp for reduction(+:t)
    for (i=0; i < n; ++i) {
        t += x[i]
    }
    #pragma omp master
    {
        printf("Slept [s]: %d\n", t);
    }
}
```

Vectorization

- Parallelism that exploits the hardware feature.
- Enables the execution of multiple iterations of the loops concurrently by means of SIMD instructions.
- Data alignment is important.

Data Alignment

- Tells the compiler to create data objects in memory on specific byte boundaries.
- Increases the efficiency of data loads and stores to and from the processor.
- Aligning consists of:
  - Aligning the base-pointer where the space is allocated for the array (or pointer).
  - Making sure the starting indices have good-alignment properties for each vectorized loop (for each thread)

Data Alignment C

- For static arrays, use compiler attributes.

```
#define ALIGNMENT __BIGGEST_ALIGNMENT__
#define ATT_ALIGN __attribute__((aligned(ALIGNMENT)))
    int a[1024] ATT_ALIGN;
```

- For dynamic arrays, use `posix_memalign` instead of `malloc`.

```
    int n = 1024;
    double *b = NULL;

    ierr = posix_memalign((void **)&b, ALIGNMENT,
                          n * sizeof(double));
    /* do something */
    if (b) {
            free(b);
            b = NULL;
    }
```

Data Alignment Fortran

- Use the directive `attributes align`.

```
integer, parameter              :: n = 1024
double precision, allocatable :: a(:)
!dir$ attributes align: 64:: a

allocate(a(n), stat=ierr)
! do something
if (allocated(a)) then
    deallocate(a)
end if
```

SIMD Construct

- To create a vectorized loop using **only** SIMD instructions.

C

```c
#pragma omp simd
for (i = 0; i < n; ++i) {
    a[i] = b[i] + c[i];
}
```

Fortran

```fortran
!$OMP simd
do i=1,n
    a(i) = b(i) + c(i)
end do
!$OMP end simd
```

SIMD Clauses

- Accepts the following clauses
  - `safelen(`*x*`)`
  - `linear(`*list*`[:`*linear-step*`])`
  - `aligned(`*list*`[:`*alignment*`])`
  - `private(`*list*`)`
  - `lastprivate(`*list*`)`
  - `reduction(`*op*`:`*list*`)`
  - `collapse(`*x*`)`

safelen

- No two iterations executed concurrently with SIMD instructions can have a greater distance in the logical iteration space than its value.

C

```c
#pragma omp simd safelen(4)
for (i = 0; i < n; ++i) {
    a[i] = a[i+4] + 1;
}
```

linear

- Declares the items to be private to a SIMD lane.
- Has a linear relationship with respect to the iteration space of a loop.

C

```c
int step = 4;
float a[N] = {0};
float sum = 0.0f;
float *p = a;

#pragma omp simd reduction(+:sum) linear(p:step)
for (int i = 0; i < N; ++i) {
   sum += *p;
   p += step;
}
```

aligned

- Declares one or more list items to be aligned to the specified number of bytes.

C

```c
#pragma omp simd aligned(a:64,b:64)
for (int i = 0; i < N; ++i) {
   a[i] = b[i] + 1;
}
```

Loop SIMD

- Combines worksharing loop construct and the SIMD contruct.
  - Parallel over threads.
  - Vectorized over SIMD.
- Construct accepts the same clases as the `for` construct.

C

```c
#pragma omp parallel \
      for simd       \
      aligned(a,b,c:64)
for (i = 0; i < n; ++i) {
    a[i] = b[i] + c[i];
}
```

Fortran

```fortran
!$OMP parallel &
!$OMP do simd  &
!$OMP aligned(a,b,c:64)
do i=1,n
    a(i) = b(i) + c(i)
end do
!$OMP end parallel do simd
```

Function SIMD

- Declare function and subroutines.
- Accepts the following clauses
  - `simdlen(`*x*`)`
  - `uniform(`*list*`)`
  - `linear(`*list*`[:`*linear-step*`])`

C

```c
#pragma declare simd uniform(fact)
double add(double a, double b, double fact)
{
    double c = 0.0;
    c = a + b + fact;
    return c;
}
```

Fortran

```fortran
function add(a, b, fact) result(c)
!$omp declare simd(add) uniform(fact)
    implicit none
    double precision :: a, b, fact, c
    c = a + b + fact
```

Accelerators

- Host-centric: the execution of an OpenMP program starts on the host device and it may offload target regions to target devices.
- If a target device is not present, or not supported, or not available, the target region is executed by the host device.
- If a construct creates a data environment, the data environment is created at the time the construct is encountered.

Target Construct

C

```c
#pragma omp target          \
            device(0)       \
            map(to:x,y)     \
            map(from:z)
#pragma omp parallel for    \
        default(none)       \
        private(i)          \
        shared(x, y, z, n)
for (i=0; i < n; ++i) {
    z[i] = x[i] + y[i];
}
```

Fortran

```fortran
!$omp target device(0)     &
!$omp        map(to:x,y)   &
!$omp        map(from:z)
!$omp parallel do          &
!$omp       default(none)  &
!$omp       private(i)     &
!$omp       shared(x, y, z, n)
    do i=1,n
        z(i) = x(i) + y(i)
    end do
```

Questions?

Online Survey

<Timothy.P.Brown@noaa.gov>

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