Topics in Computing for Astronomy:
Parallel Programming with OpenMP (I)

Rich Townsend, University of Wisconsin-Madison

Preliminaries

- The Mad SDK (contains gfortran, an OpenMP-capable Fortran 90/95/2003/2008 compiler)

  http://www.astro.wisc.edu/~townsend/static.php?ref=madsdk

- This talk & accompanying code examples:

  http://www.astro.wisc.edu/~townsend/static.php?ref=talks

What is OpenMP?

- An Application Programming Interface (API) for writing multithreaded programs
- Consists of a set of compiler directives, library routines and environment variables
- Supports Fortran, C and C++
- Developed by vendors (AMD, IBM, Intel, ...)
- Mainly targeted at Symmetric Multiprocessing systems

What is a Symmetric Multiprocessing (SMP)?

- A multiprocessor system with
  - centralized, shared memory
  - a single operating system
  - two or more homogeneous processors
- Modern desktops/laptops are SMP systems:
  - Multiple cores in each physical processor
  - Multiple physical processors

What is Multithreading?

- The ability of a program to have multiple, independent *threads* executing different sequences of instructions
- The threads can access the resources (e.g., memory) of the parent process
- The threads run concurrently on a multiprocessor systems

OpenMP Core Syntax

- Constructs use compiler directives specified using special Fortran comments:

Fortran 77

```
C$omp parallel do
```

Fortran 90+

```
!$omp parallel
```

- Most constructs apply to a "structured block" with one point of entry and one point of exit
- Additional library functions and subroutines accessed through the `omp_lib` module

Example: Hello World

hello_world.f90

```
program hello_world

  use omp_lib
  implicit none

  !$omp parallel num_threads(4)
  print *, 'Hello from thread', omp_get_thread_num()
  !$omp end parallel

end program hello_world
```

```
% gfortran -fopenmp -o hello_world hello_world.f90
% ./hello_world
 Hello from thread           0
 Hello from thread           2
 Hello from thread           3
 Hello from thread           1
```

Example: Hello World

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Make OpenMP routines available

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Make OpenMP routines available

Start a parallel region with 4 threads

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Make OpenMP routines available

Start a parallel region with 4 threads

Get the ID of the thread

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end program hell
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Make OpenMP routines available

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Get the ID of the thread

Tell gfortran to recognize !$omp directives

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% gfortran -fopenmp -o hello_world hello_world.f90
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Start a parallel region with 4 threads

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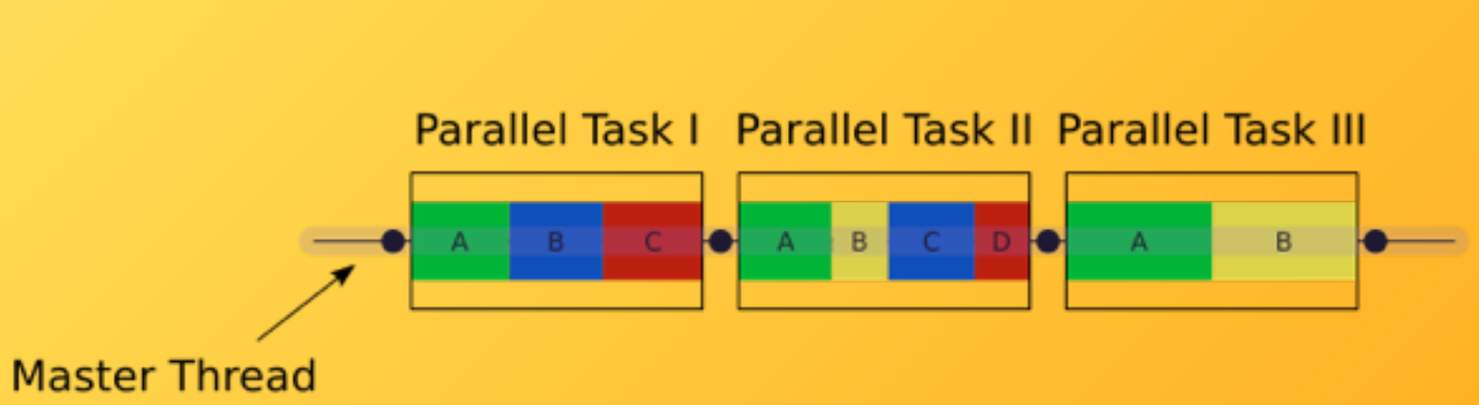
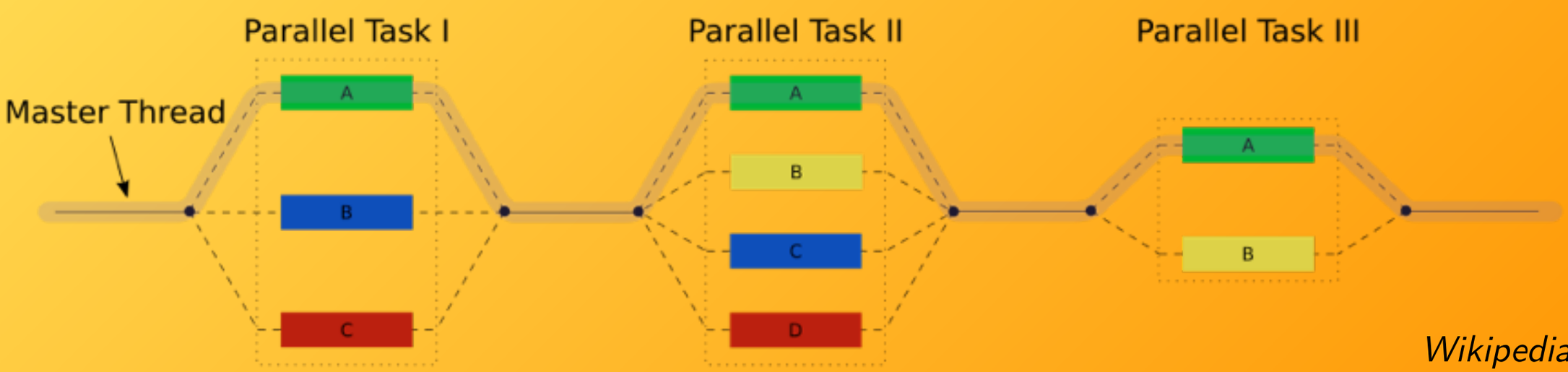
 Hello from thread           3
 Hello from thread           1
```

Not sequential — OpenMP does not guarantee execution order!

The Fork-Join Thread Model

- At the start of a program, there is a single thread — the *master thread*
- When entering a parallel region, the master thread 'forks' into a team of threads
- When exiting a parallel region, the team joins back into a single master thread





Wikipedia

Sharing Variables

hello_world_shared.f90

```
program hello_world_shared

  use omp_lib
  implicit none

  integer :: id

  !$omp parallel num_threads(4)
  id = omp_get_thread_num()
  print *, 'Hello from thread', id
  !$omp end parallel

end program hello_world_shared
```

This overwrites the same memory location!

Sharing Variables

hello_world_shared.f90

```
program hello_world_shared

  use omp_lib
  implicit none

  integer :: id

  !$omp parallel num_threads(4)
  id = omp_get_thread_num()
  print *, 'Hello from thread', id
  !$omp end parallel

end program hello_world_shared
```

The id variable is by default shared amongst threads

This overwrites the same memory location!

Not Sharing Variables

hello_world_private.f90

```
program hello_world_private

  use omp_lib
  implicit none

  integer :: id

  !$omp parallel num_threads(4) private(id)
  id = omp_get_thread_num()
  print *, 'Hello from thread', id
  !$omp end parallel

end program hello_world_private
```

Not Sharing Variables

hello_world_private.f90

```
program hello_world_private

  use omp_lib
  implicit none

  integer :: id

  !$omp parallel num_threads(4) private(id)
  id = omp_get_thread_num()
  print *, 'Hello from thread', id
  !$omp end parallel

end program hello_world_private
```

The `id` variable is private; each thread has its own copy

Read/Write Races

count_threads.f90

```
program count_threads

  use omp_lib
  implicit none

  integer :: n

  n = 0

  !$omp parallel num_threads(4)
  n = n + 1
  !$omp end parallel

  print *,'There were', n, 'threads'

end program count_threads
```

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  use omp_lib
  implicit none

  integer :: n

  n = 0

  !$omp parall  num_threads(4)
  n = n + 1
  !$omp end parallel

  print *,'There were', n, 'threads'

end program count_threads
```

Bad: another thread could update n between read and write

Atomic Operations

count_threads_atomic.f90

```
program count_threads_atomic

  use omp_lib
  implicit none

  integer :: n

  n = 0

  !$omp parallel num_threads(4)
  !$omp atomic
  n = n + 1
  !$omp end parallel

  print *,'There were', n, 'threads'

end program count_threads_atomic
```

Atomic Operations

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  use omp_lib
  implicit none

  integer :: n

  n = 0

  !$omp parallel num_threads(4)
  !$omp atomic
  n = n + 1
  !$omp end parallel

  print *,'There were', n, 'threads'

end program count_threads_atomic
```

atomic directive:
the read/write in the
following operation must be
executed as one

Synchronization Directives

- `!$omp atomic` is an example of a *synchronization directive*
- Other examples:
  - `!$omp critical` — only execute on one thread at a time
  - `!$omp master` — only execute on master thread
  - `!$omp barrier` — wait for all threads

Sharing the Load

square_nums.f90

```
program square_nums

  use omp_lib
  implicit none

  integer :: i, j(4)

  !$omp parallel num_threads(4)
  i = omp_get_thread_num() + 1
  j(i) = i**2
  !$omp end parallel

  print *,'Square numbers:', j

end program square_nums
```

Sharing the Load

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program square_nums

  use omp_lib
  implicit none

  integer :: i, j(4)

  !$omp parallel num_threads(4)
  i = omp_get_thread_num() + 1
  j(i) = i**2
  !$omp end parallel

  print *,'Square numbers:', j

end program square_nums
```

Calculate array index from thread id

Parallelizing DO loops

square_nums_do.f90

```
program square_nums_do

  use omp_lib
  implicit none

  integer :: i, j(13)

  !$omp parallel num_threads(4)
  !$omp do
  do i = 1, SIZE(j)
    j(i) = i**2
  enddo
  !$omp end parallel

  print *,'Square numbers:', j

end program square_nums_do
```

Parallelizing DO loops

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program square_nums_do

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  integer :: i, j(13)

  !$omp parallel num_threads(4)
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  do i = 1, SIZE(j)
    j(i) = i**2
  enddo
  !$omp end parallel

  print *,'Square numbers:', j

end program square_nums_do
```

Will work with array of any size

Parallelizing DO loops

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program square_nums_do

  use omp_lib
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  integer :: i, j(13)

  !$omp parallel num_threads(4)
  !$omp do
  do i = 1, SIZE(j)
    j(i) = i**2
  enddo
  !$omp end parallel

  print *,'Square numbers:', j

end program square_nums_do
```

Will work with array of any size

do directive distributes loop iterations amongst threads

A Shorthand: parallel do

square_nums_pardo.f90

```
program square_nums_pardo

  use omp_lib
  implicit none

  integer :: i, j(13)

  !$omp parallel do num_threads(4)
  do i = 1, SIZE(j)
    j(i) = i**2
  enddo
  !$omp end parallel do

  print *,'Square numbers:', j

end program square_nums_pardo
```

A Shorthand: parallel do

square_nums_pardo.f90

```
program square_nums_pardo

  use omp_lib
  implicit none

  integer :: i, j(13)

  !$omp parallel do num_threads(4)
  do i = 1, SIZE(j)
    j(i) = i**2
  enddo
  !$omp end parallel do

  print *,'Square numbers:', j

end program square_nums_pardo
```

parallel do
directive creates parallel region
AND distributes loop iterations
amongst threads

Work-Sharing Constructs

- `!$omp do` is an example of a work-sharing construct
- A work-sharing construct divides the execution of the enclosed region among the members of the thread team that encounters it

- Other examples:
  - `!$omp sections` — divide multiple enclosed blocks amongst threads of team
  - `!$omp workshare` — divide single enclosed block amongst threads of team
  - `!$omp single` — execute all work on a single thread

The workshare Construct

square_nums_workshr.f90

```
program square_nums_workshr

  use omp_lib
  implicit none

  integer :: i, j(13)

  j = [(i,i=1,SIZE(j))]

  !$omp parallel workshare num_threads(4)
  j = j**2
  !$omp end parallel workshare

  print *,'Square numbers:', j

end program square_nums_workshr
```

The workshare Construct

square_nums_workshr.f90

```
program square_nums_workshr

  use omp_lib
  implicit none

  integer :: i, j(13)

  j = [(i,i=1,SIZE(j))]

  !$omp parallel workshare num_threads(4)
  j = j**2
  !$omp end parallel workshare

  print *,'Square numbers:', j

end program square_nums_workshr
```

Initialize j using an array assignment

The workshare Construct

square_nums_workshr.f90

```
program square_nums_workshr

  use omp_lib
  implicit none

  integer :: i, j(13)

  j = [(i,i=1,SIZE(j))]

  !$omp parallel workshare num_threads(4)
  j = j**2
  !$omp end parallel workshare

  print *,'Square numbers:', j

end program square_nums_workshr
```

Initialize j using an array assignment

These array arithmetic/assignment operations are distributed amongst the team

Restrictions on `workshare` Constructs

- Only the following operations permitted:
  - array assignments
  - scalar assignments
  - FORALL statements
  - FORALL constructs
  - WHERE statements
  - WHERE constructs
  - atomic constructs
  - critical constructs
  - parallel constructs

The sections Construct

hello_sections.f90

```
program hello_sections

  use omp_lib
  implicit none

  !$omp parallel sections num_threads(4)
  !$omp section
  print *,'Hello from thread', omp_get_thread_num()
  !$omp section
  print *,'Hola from thread', omp_get_thread_num()
  !$omp section
  print *,'Aloha from thread', omp_get_thread_num()
  !$omp end parallel sections

end program hello_sections
```

The sections Construct

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```
program hello_sections

  use omp_lib
  implicit none

  !$omp parallel se                    reads(4)
  !$omp section
  print *,'Hello from thread', omp_get_thread_num()
  !$omp section
  print *,'Hola from thread', omp_get_thread_num()
  !$omp section
  print *,'Aloha from thread', omp_get_thread_num()
  !$omp end parallel sections

end program hello_sections
```

Each block delimited by `!$omp section` runs on a separate thread