Parallel Programming with Compiler Directives
— OpenMP —

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ASCI Course A24

A Programmer's Guide for
Modern High-Performance Computing Architectures

Parallel Programming with Compiler Directives: OpenMP

Design Rationale of OpenMP

Ideal:

- Automatic parallelisation of sequential code.
- No additional parallelisation effort for development, debugging, maintenance, etc.

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Problem:

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- Compilers must be conservative in their assumptions.

Way out:

- Take or write ordinary sequential program.
- Add annotations/pragmas/compiler directives that guide parallelisation.
- Let the compiler generate the corresponding code.

Short History of OpenMP

Towards OpenMP:

- Mid 1980s: First commercial SMPs appear.
  - ANSI standard X3H5 (not adopted)
- Late 1980s to early 1990s:
  - Distributed memory architectures prevail.
- Early 1990s until today:
  - Shared memory architectures significantly gain popularity.
  - Different vendor-specific compiler extensions.
- 1996/97:
  - Development of a new industry standard: OpenMP
  - Actively supported by all major hardware vendors: Intel, HP, SGI, IBM, SUN, Compaq, ...
  - OpenMP Architectural Review Board: http://www.openmp.org/

Short History of OpenMP

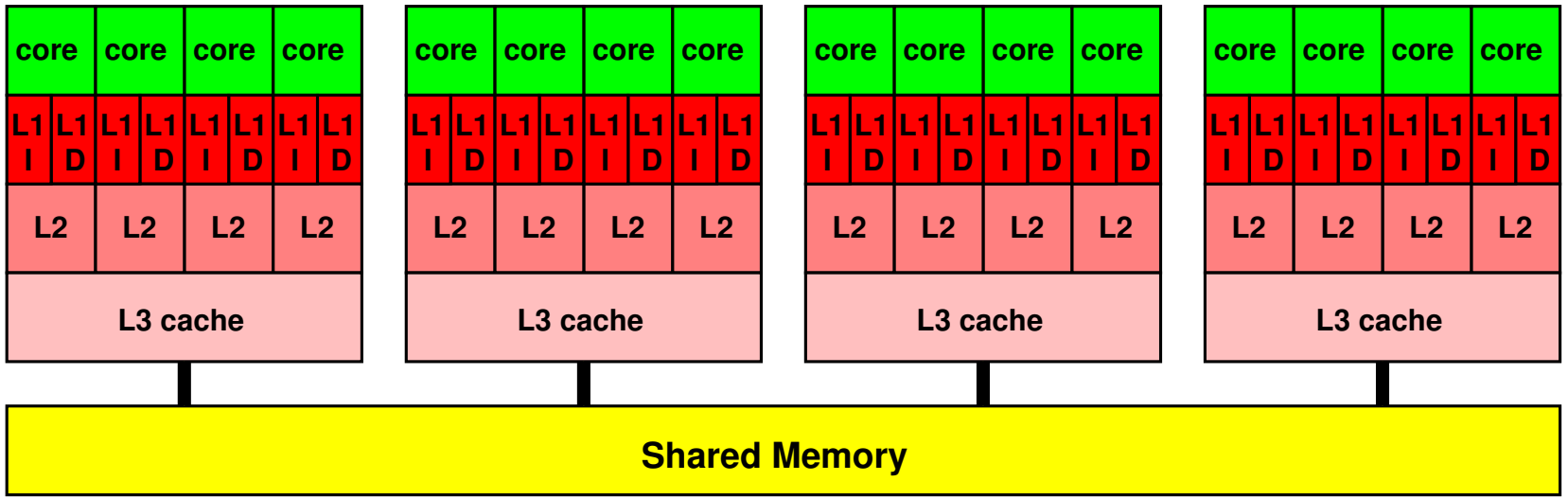
OpenMP Standardisation:

- 1996 : Fortran Version 1.0
- 1998 : C/C++ Version 1.0
- 1999 : Fortran Version 1.1
- 2000 : Fortran Version 2.0
- 2002 : C/C++ Version 2.0
- 2005 : Joint Version 2.5
- 2008 : Joint Version 3.0
- 2011 : Joint Version 3.1

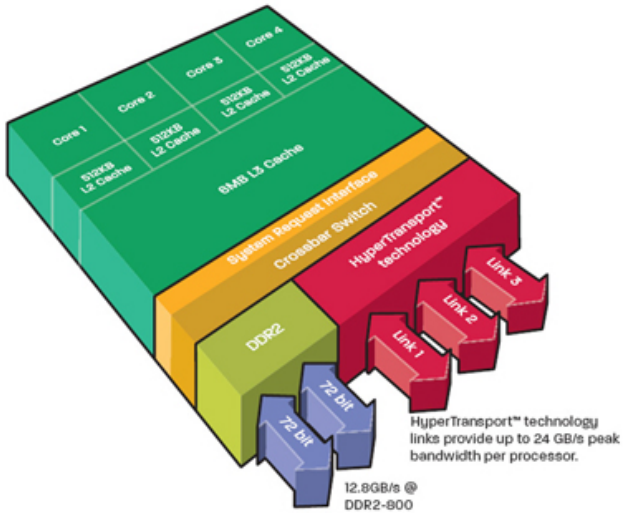
OpenMP Architectural Model

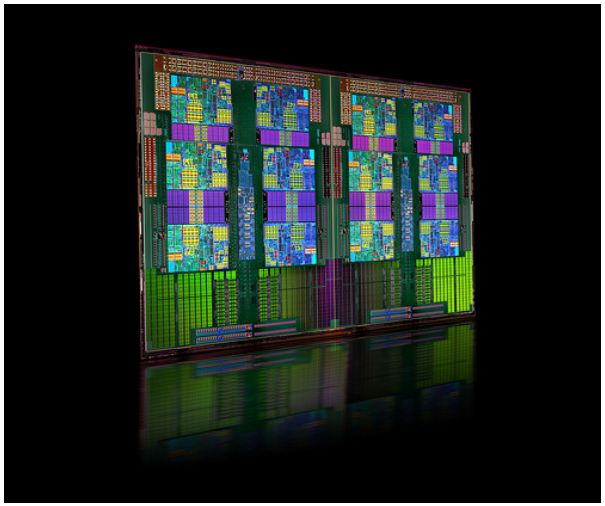
Characteristics:

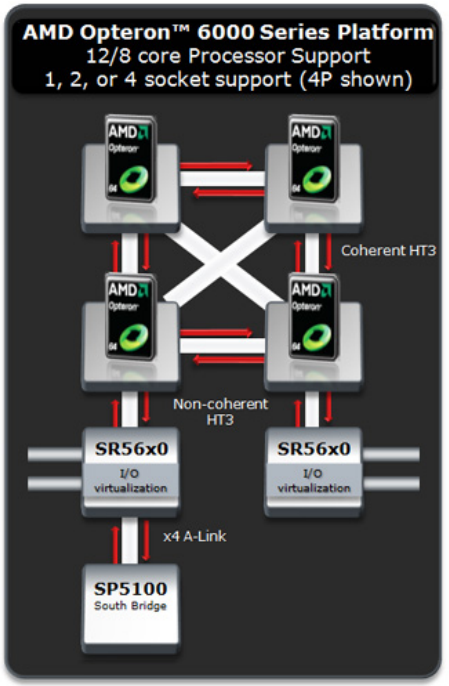
- Multiple processors
- Multiple cores
- Shared memory (with cache coherence)

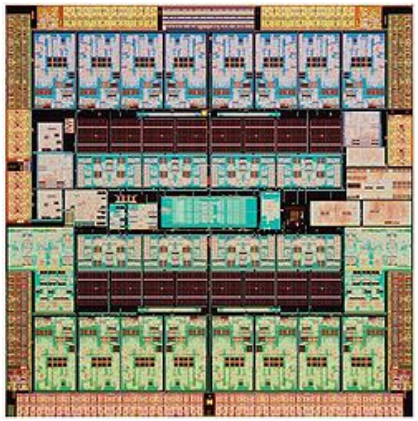


Potential Target Architectures









- Intel/AMD standard multicores
- Symmetric multiprocessors
- Oracle Niagara series

OpenMP at a Glance

OpenMP as a programming interface:

- Compiler directives
- Library functions
- Environment variables

C/C++ version:

```
#pragma omp name [clause]*
structured block
```

Fortran version:

```
!$ OMP name [ clause [, clause]*]
code block
!$ OMP END name
```

Hello World with OpenMP

```
#include "omp.h"
#include <stdio.h>

int main()
{
  printf( "Starting execution with %d threads:\n",
          omp_get_num_threads());

  #pragma omp parallel
  {
    printf( "Hello world says thread %d of %d.\n",
            omp_get_thread_num(),
            omp_get_num_threads());
  }

  printf( "Execution of %d threads terminated.\n",
          omp_get_num_threads());

  return( 0);
}
```

Hello World with OpenMP

Compilation:

```
gcc -fopenmp hello_world.c
```

Output using 4 threads:

```
Starting execution with 1 threads:
Hello world says thread 2 of 4.
Hello world says thread 3 of 4.
Hello world says thread 1 of 4.
Hello world says thread 0 of 4.
Execution of 1 threads terminated.
```

Hello World with OpenMP

Using 4 threads:

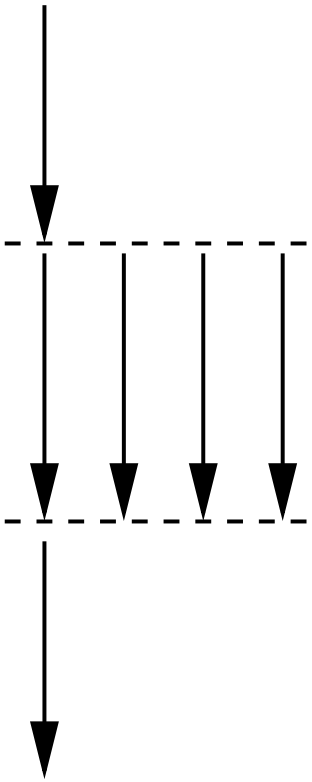
```
Starting execution with 1 threads:
Hello world says thread 2 of 4.
Hello world says thread 3 of 4.
Hello world says thread 1 of 4.
Hello world says thread 0 of 4.
Execution of 1 threads terminated.
```

Who determines number of threads ?

- Environment variable: `export OMP_NUM_THREADS=4`
- Library function: `void omp_set_num_threads( int)`

OpenMP Execution Model

Classical Fork/Join:



Master thread executes serial code.

Master thread encounters parallel directive.

Master and slave threads concurrently execute parallel block.

Implicit barrier, wait for all threads to finish.

Master thread resumes serial execution.

Parallel Programming with Compiler Directives: OpenMP

Simple Loop Parallelisation

Example: element-wise vector product:

```
void elem_prod( double *c, double *a, double *b, int len)
{
  int i;

  #pragma omp parallel for

  for (i=0; i<len; i++)
  {
    c[i] = a[i] * b[i];
  }
}
```

Simple Loop Parallelisation

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```

Prerequisite:

- No data dependence between any two iterations.

Simple Loop Parallelisation

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  }
}
```

Prerequisite:

- No data dependence between any two iterations.
- **Caution: YOU claim this property !!**

Directive #pragma omp parallel for

What the compiler directive does for you:

- It starts additional worker threads depending on `OMP_NUM_THREADS`.
- It divides the iteration space among all threads.
- It lets all threads execute loop restricted to their mutually disjoint subsets.
- It synchronizes all threads at an implicit barrier.
- It terminates worker threads.

Directive #pragma omp parallel for

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- It divides the iteration space among all threads.
- It lets all threads execute loop restricted to their mutually disjoint subsets.
- It synchronizes all threads at an implicit barrier.
- It terminates worker threads.

Restrictions:

- The directive must directly precede for-loop.
- The for-loop must match a constrained pattern.
- The trip-count of the for-loop must be known in advance.

Shared and Private Variables

Example:

```
#pragma omp parallel for

for (i=0; i<len; i++)
{
  res[i] = a[i] * b[i];
}
```

- Shared variable: one instance for all threads
- Private variable: one instance for each thread

Shared and Private Variables

Example:

```
#pragma omp parallel for

for (i=0; i<len; i++)
{
  res[i] = a[i] * b[i];
}
```

Who decides that res, a, b, and len are shared variables, whereas i is private ??

Shared and Private Variables

Example:

```
#pragma omp parallel for

for (i=0; i<len; i++)
{
  res[i] = a[i] * b[i];
}
```

Who decides that res, a, b, and len are shared variables, whereas i is private ??

Default rules:

- All variables are **shared**.
- Only loop variables of parallel loops are **private**.

Parallelisation of a Less Simple Loop

Mandelbrot set:

```
double x, y;
int i, j, max = 200;
int depth[M,N];
...
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
} }
```

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```

Properties to check:

- No data dependencies between loop iterations ?

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Properties to check:

- No data dependencies between loop iterations ? YES !
- Trip-count known in advance ?

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Properties to check:

- No data dependencies between loop iterations ? YES !
- Trip-count known in advance ? YES !
- Function `mandelval` without side-effects ?

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- Function `mandelval` without side-effects ? YES !
- Only loop variable `i` needs to be private ?

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    depth[i,j] = mandelval( x, y, max);
} }
```

Properties to check:

- No data dependencies between loop iterations ? YES !
- Trip-count known in advance ? YES !
- Function `mandelval` without side-effects ? YES !
- Only loop variable `i` needs to be private ? NO !!!!
  Check `x,y,j`

Parallelisation of a Less Simple Loop

Mandelbrot set:

```
double x, y;
int i, j, max = 200;
int depth[M,N];
...
#pragma omp parallel for private( x, y, j)
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
} }
```

Private clause:

- Directives may be refined by *clauses*.
- Private clause allows to tag any variable as private.
- Caution: private variables are **not** initialised outside parallel section !!

Parallelisation of a Less, Less Simple Loop

Mandelbrot set with additional counter:

```
int total = 0;
...
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
    total = total + depth[i,j];
} }
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Parallelisation of a Less, Less Simple Loop

Mandelbrot set with additional counter:

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int total = 0;
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for (i=0; i<M; i++) {
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    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
    total = total + depth[i,j];
} }
```

Problems:

- New variable `total` introduces data dependence.
- Data dependence could be ignored due to associativity.
- New variable `total` must be shared.
- Incrementation of `total` must avoid race condition.

Parallelisation of a Less, Less Simple Loop

Mandelbrot set with additional counter:

```
int total = 0;
...
#pragma omp parallel for private( x, y, j)
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);

    #pragma omp critical
    {
       total = total + depth[i,j];
    }
  }
}
```

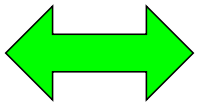
Critical Regions

The `critical` directive:

- Directive must immediately precede new statement block.
- Statement block is executed without interleaving.
- Directive implements critical region.

Equivalence:

```
#pragma omp critical
{
  <statements>
}
```



```
pthread_mutex_lock( &lock);
  <statements>
pthread_mutex_unlock( &lock);
```

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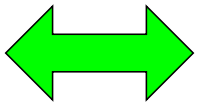
```



```
pthread_mutex_lock( &lock);
  <statements>
pthread_mutex_unlock( &lock);
```

Disadvantage:

- All critical regions in entire program are synchronised.
- Unnecessary overhead.

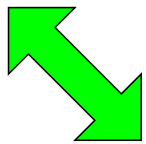
Critical Regions

The named `critical` directive

- Critical regions may be associated with names.
- Critical regions with identical names are synchronised.
- Critical regions with different names are executed concurrently.

Equivalence:

```
#pragma omp critical (name)
{
  <statements>
}
```



```
pthread_mutex_lock( &name_lock);
  <statements>
pthread_mutex_unlock( &name_lock);
```

Reduction Operations

Specific solution: reduction clause

```
#pragma omp parallel for private( x, y, i, j) \
                         reduction(+:total)
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
    total = total + depth[i,j];
  }
}
```

Properties:

- Reduction clause only supports built-in reduction operations:
  `+, *, ^, &, |, &&, ||, min, max`.
- User-defined reductions only supported via critical regions.
- Bit accuracy not guaranteed.

Shared and Private Variables Reloaded

Shared variables:

- One instance shared between sequential and parallel execution.
- Value unaffected by transition.

Private variables:

- One instance during sequential execution.
- One instance per worker thread during parallel execution.
- No exchange of values.

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New: Firstprivate variables:

- Like private variables, but ...
- Worker thread instances initialised with master thread value.

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- One instance shared between sequential and parallel execution.
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- No exchange of values.

New: Firstprivate variables:

- Like private variables, but ...
- Worker thread instances initialised with master thread value.

New: Lastprivate variables:

- Like private variables, but ...
- Master thread instance updated to value of worker thread instance that executes the last (in sequential order) iteration.

Shared and Private Variables Reloaded

Example:

```
int a=1, b=2, c=3, d=4, e=5;

#pragma omp parallel for private( a) \
                         firstprivate( b,d) \
                         lastprivate( c,d)
for (i=0; i<10; i++) {
  // before first iteration:
  //   a : ?? | b : ?? | c : ?? | d : ?? | e: ??
  a++; b++; c=7; d++;
}

//  a : ?? | b : ?? | c : ?? | d : ?? | e: ??
```

Shared and Private Variables Reloaded

Example:

```
int a=1, b=2, c=3, d=4, e=5;

#pragma omp parallel for private( a) \
                         firstprivate( b,d) \
                         lastprivate( c,d)
for (i=0; i<10; i++) {
  // before first iteration:
  //  a : undef | b : 2 | c : undef | d : 4 | e: 5
  a++; b++; c=7; d++;
}

//  a : 1 | b : 2 | c : 7 | d : ?? | e: 5
```

Note:

- The value of d depends on the number of iterations executed by the thread that is assigned iteration i=9 by the OpenMP loop scheduler.

Conditional Parallelisation

Problem:

- Parallel execution of a loop incurs overhead:
  - creation of worker threads
  - scheduling
  - synchronisation barrier
- This overhead must be outweighed by sufficient workload.
- Workload depends on
  - loop body,
  - trip count.

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- Workload depends on
  - loop body,
  - trip count.

Example:

```
if (len < 1000) {
  for (i=0; i<len; i++)
  {
    res[i] = a[i] * b[i];
  }
}
else {
  #pragma omp parallel for
  for (i=0; i<len; i++)
  {
    res[i] = a[i] * b[i];
  }
}
```

Conditional Parallelisation

Introducing the `if`-clause:

```
if (len < 1000) {
  for (i=0; i<len; i++) {
    res[i] = a[i] * b[i];
  }
}
else {
  #pragma omp parallel for
  for (i=0; i<len; i++) {
    res[i] = a[i] * b[i];
  }
}
```

```
#pragma omp parallel for if (len >= 1000)
for (i=0; i<len; i++) {
  res[i] = a[i] * b[i];
}
```

Parallel Programming with Compiler Directives: OpenMP

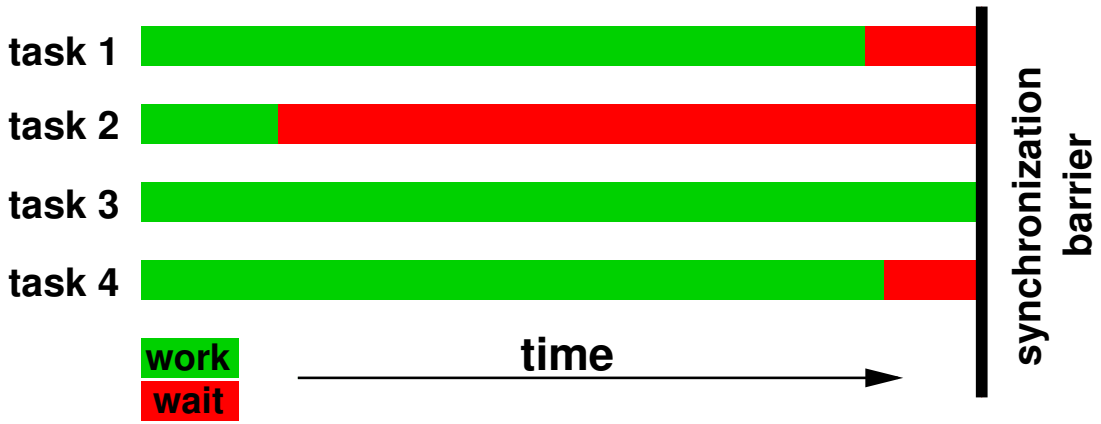
Loop Scheduling

Definition:

- Loop scheduling determines which iterations are executed by which thread.

Aim:

- Equal workload distribution



Loop Scheduling

Problem:

- Different situations require different techniques

The `schedule` clause:

```
#pragma omp parallel for schedule( <type> [, <chunk>])
for (...)
{
   ...
}
```

Properties:

- Clause selects one out of a set of scheduling techniques.
- Optionally, a chunk size can be specified.
- Default chunk size depends on scheduling technique.

Loop Scheduling

Static scheduling:

```
#pragma omp parallel for schedule( static)
```

- Loop is subdivided into as many chunks as threads exist.
- Often called block scheduling.

Loop Scheduling

Static scheduling:

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- Often called block scheduling.

Static scheduling with chunk size:

```
#pragma omp parallel for schedule( static , <n>)
```

- Loop is subdivided into chunks of n iterations.
- Chunks are assigned to threads in a round-robin fashion.
- Also called block-cyclic scheduling.

Loop Scheduling

Dynamic scheduling:

```
#pragma omp parallel for schedule( dynamic, <n>)
```

- Loop is subdivided into chunks of n iterations.
- Chunks are dynamically assigned to threads on their demand.
- Also called self scheduling.
- Default chunk size: 1 iteration.

Properties:

- Allows for dynamic load distribution and adjustment.
- Requires additional synchronization.
- Generates more overhead than static scheduling.

Loop Scheduling

Dilemma of chunk size selection:

- Small chunk sizes mean good load balancing, but high synchronisation overhead.
- Large chunk sizes reduce synchronisation overhead, but result in poor load balancing.

Loop Scheduling

Dilemma of chunk size selection:

- Small chunk sizes mean good load balancing, but high synchronisation overhead.
- Large chunk sizes reduce synchronisation overhead, but result in poor load balancing.

Rationale of guided scheduling:

- In the beginning, large chunks keep synchronisation overhead small.
- When approaching the final barrier, small chunks balance workload.

Loop Scheduling

Guided scheduling:

```
#pragma omp parallel for schedule( guided, <n>)
```

- Chunks are dynamically assigned to threads on their demand.
- Initial chunk size is implementation dependent.
- Chunk size decreases exponentially with every assignment.
- Also called guided self scheduling.
- Minimum chunk size: n (default: 1)

Example:

- Total number of iterations: 250
- Initial / minimal chunk size: 50 / 5
- Current chunk size: 80% of last chunk size:
  50 – 40 – 32 – 26 – 21 – 17 – 14 – 12 – 10 – 8 – 6 – 5 – 5 – 4

Loop Scheduling

Can't decide? Use runtime scheduling:

```
#pragma omp parallel for schedule( runtime)
```

- Choose scheduling at runtime
- Environment variable `OMP_SCHEDULE`
- Library function

  ```
  void omp_set_schedule(omp_sched_t kind, int modifier)
  ```

For the records:

```
typedef enum omp_sched_t {
  omp_sched_static = 1,
  omp_sched_dynamic = 2,
  omp_sched_guided = 3,
  omp_sched_auto = 4
} omp_sched_t;
```

Mandelbrot Reloaded

Previous code:

```
double x, y;
int i, j, max = 200;
int depth[M,N];
...
#pragma omp parallel for private( i, j, x, y)
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
} }
```

Which scheduling ?

Mandelbrot Reloaded

With guided scheduling:

```
double x, y;
int i, j, max = 200;
int depth[M,N];
...
#pragma omp parallel for private( i, j, x, y) scheduling( guided)
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
} }
```

What if M is small ?

Mandelbrot Reloaded

With collapse directive:

```
double x, y;
int i, j, max = 200;
int depth[M,N];
...
#pragma omp parallel for private( i, j, x, y) \
                         scheduling( guided) \
                         collapse( 2)
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
} }
```

Collapse directive:

- Collapses multi-dimensional iteration space into single one subject to OpenMP scheduling
- Requires perfect loop nest
- Advantage: more control/flexibility for OpenMP

Parallel Programming with Compiler Directives: OpenMP

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The End

Questions ?