Programming Multi-Core Systems with OpenMP

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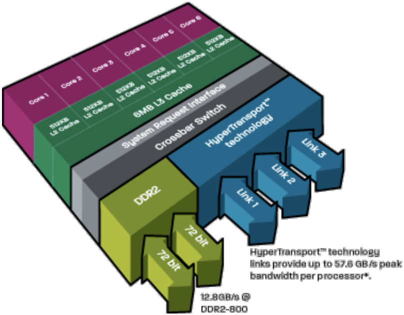
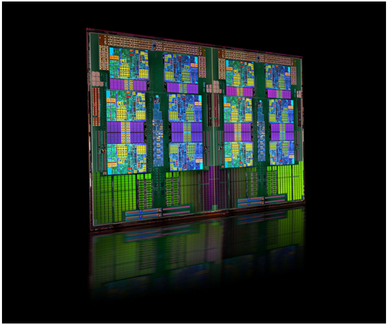
Programming Multi-Core Systems with OpenMP

Target Multi-core Systems

Small-scale general-purpose (x86) multicore processors:

- Intel / AMD commodity processors with 2, 4, 6 or 8 cores
- potentially hyperthreaded

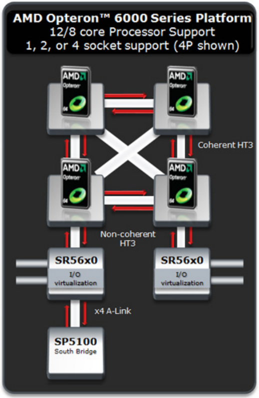




Target Multi-core Systems

Medium-scale server systems:

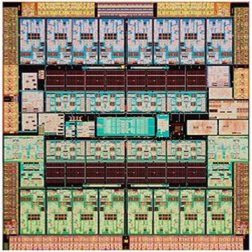
- multiple (2 or 4 in practice) identical processors
- each processor with several cores
- high bandwidth data path between processors



Target Multi-core Systems

Large-scale shared address space compute systems:

- large number of slightly simpler cores
- SUN MicroSystems / Oracle Niagara / UltraSparc T series
- up to 512 hardware threads (T3-4 server)



Design Rationale of OpenMP

Ideal:

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

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- Data dependences are difficult to assess.
- Compilers must be conservative in their assumptions.

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- Data dependences are difficult to assess.
- 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.

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:

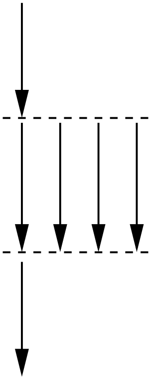
```
Starting execution with 1 threads:
Hello world says thread 2 of 4.
Hello world says thread 3 of 4.
Hello world says thread 1 of 4.
Hello world says thread 0 of 4.
Execution of 1 threads terminated.
```

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.

Programming Multi-Core Systems with 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.

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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.

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- 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

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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 ??

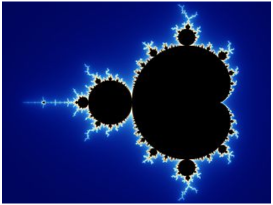
Default rules:

- 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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- 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 ?

Parallelisation of a Less Simple Loop

Function mandelval:

```
int mandelval( double xx, double yy, int max)
{
  int i =0;
  double x = xx, y = yy;

  while (x*x + y*y <= 4.0 && i < max) {
    x = x*x - y*y + xx;
    y = x*y + x*y + yy;
    i++;
  }

  return i;
}
```

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    x = (double) i / (double) M;
    y = (double) j / (double) N;
    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) shared( M, N, max)
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 us to tag any variable as private.
- Caution: private variables are **not** initialised outside parallel section !!
- Shared clause allows us to explicitly mark shared variables.

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];
} }
```

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];
} }
```

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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- Directive implements critical region.

Equivalence:

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

⟺

```
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: `+, *, ^, &, |, &&, ||`.
- 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.

Shared and Private Variables Reloaded

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- 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.

New: Firstprivate variables:

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

Shared and Private Variables Reloaded

Example:

```
int a=1, b=2, c=3

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

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

Shared and Private Variables Reloaded

Example:

```
int a=1, b=2, c=3

#pragma omp parallel for private( a) \
                         firstprivate( b) \
                         shared( c)
for (i=0; i<10; i++) {
  // before first iteration:
  //  a : undef | b : 2 | c : undef
  a++; b++; c=i;
}

//  a : 1 | b : 2 | c : undef
```

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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  - scheduling
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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];
}
```

Programming Multi-Core Systems with OpenMP

OpenMP at a Glance

Loop Parallelization

Scheduling

Outlook

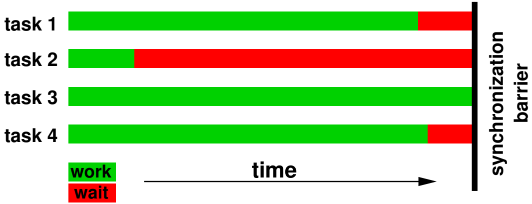
Loop Scheduling

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

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```

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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

Programming Multi-Core Systems with OpenMP

What's More ?

More in OpenMP-2:

- Decouple parallel regions from work sharing
- Control synchronisation barriers
- Task parallel sections
- Low-level locks and condition variables
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More information:

- www.openmp.org

The End: Questions ?