Multi-Core Programming with OpenMP

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Outline of the Day

- Multi-core computer architecture (brief)
- OpenMP — the Basics
- Lunch Break
- OpenMP — the Advanced Story

Generic Multi-Core Architectures

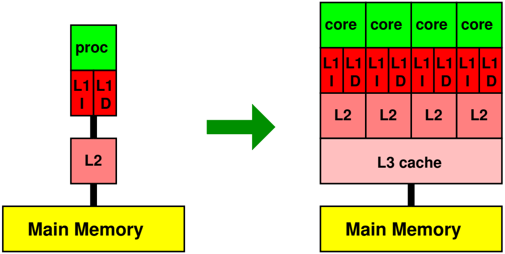
What we are talking about:

- Bread and butter multi-core processors
- Intel XEON family
- AMD Opteron family
- maybe Oracle T3/T4 (Niagara)

Generic Multi-Core Architectures

Characteristics:

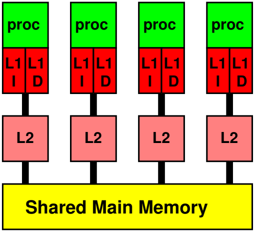
- Consequence of Murphy's Law: abundance of transistors
- Put multiple fully-fledged previous generation processors on a single die.
- Add generous caches
- Hardware cache coherence



Generic Multi-Core Architectures

Symmetric multiprocessing:

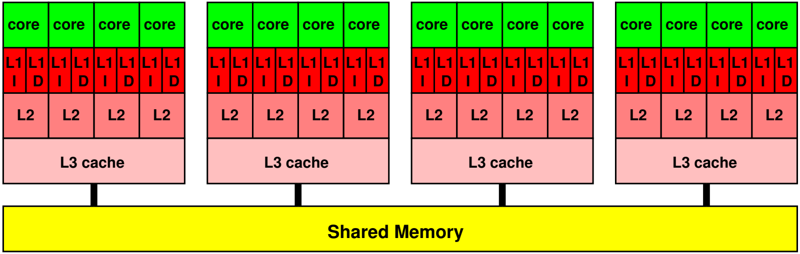
- Idea dates back to 1980s
- Assemble multiple processors on one board, 2-way or 4way
- Processor-local caches
- Shared main memory
- Hardware cache coherence



Generic Multi-Core Architectures

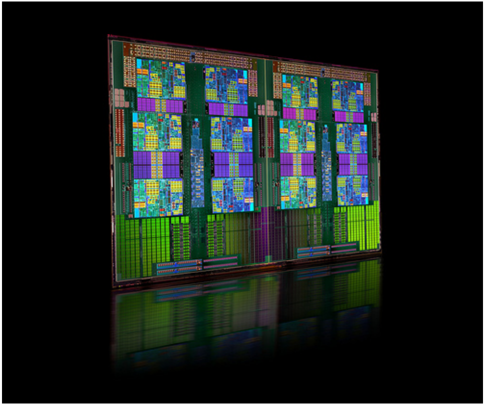
Multi-core symmetric multiprocessors:

- Combining symmetric multiprocessing with multi-core processors
- Unprecedented parallelism on single board
  - 48 AMD Opteron cores
  - 24 hyperthreaded Intel Xeon cores
- Hardware cache coherence



12-core AMD Opteron

One chip, two dies:



A Note on Hyperthreading

Idea:

- Duplicate architectural state: (control) registers
- Do not duplicate functional units
- Let one core appear as two logical cores to the OS
- Make more efficient use of resources by computing two streams of instructions simultaneously
- If one stalls the other takes over

A Note on Hyperthreading

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- Do not duplicate functional units
- Let one core appear as two logical cores to the OS
- Make more efficient use of resources by computing two streams of instructions simultaneously
- If one stalls the other takes over

Disadvantage:

- Requires the right instruction mix
- Together with symmetric multithreading OS must have specific support for hyperthreading instead of just seeing two cores
- Cache thrashing

How to program such systems

?

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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- 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

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:

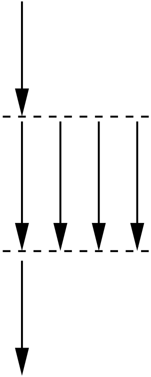
```
Starting execution with 1 threads:
Hello world says thread 2 of 4.
Hello world says thread 3 of 4.
Hello world says thread 1 of 4.
Hello world says thread 0 of 4.
Execution of 1 threads terminated.
```

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.

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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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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}
```

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:

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- Trip-count known in advance ?

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- Function `mandelval` without side-effects ?

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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 ? 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];
} }
```

Parallelisation of a Less, Less Simple Loop

Mandelbrot set with additional counter:

```
int total = 0;
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  for (j=0; j<N; j++) {
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    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*.

What is a race condition ?

Note: Adding two values is not atomic

Thread 1:

```
...
load  reg1 <= &depth
load  reg2 <= &total
add   reg1, reg2 => reg1
store reg1 => &total
...
```

What is a race condition ?

Note: Adding two values is not atomic

Thread 1:

```
...
load  reg1 <= &depth
load  reg2 <= &total
add   reg1, reg2 => reg1
store reg1 => &total
...
```

Thread 2:

```
...
load  reg1 <= &depth
load  reg2 <= &total
add   reg1, reg2 => reg1
store reg1 => &total
...
```

Problem:

- Threads operate with any interleaving.
- If different interleavings cause different results, we have a race condition.
- Program behaves non-deterministically.

What is a race condition ?

Note: Adding two values is not atomic

Thread 1:

```
...
load  reg1 <= &depth
load  reg2 <= &total
add   reg1, reg2 => reg1
store reg1 => &total
...
```

Thread 2:

```
...
load  reg1 <= &depth
load  reg2 <= &total
add   reg1, reg2 => reg1
store reg1 => &total
...
```

Solution:

- We must identify critical regions: sequences of instructions that must be executed without interleaving.
- We must establish mutual exclusion between critical regions.

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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⟺

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pthread_mutex_lock( &lock);
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```

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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New: Firstprivate variables:

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

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- 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.

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++) {
  //  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.

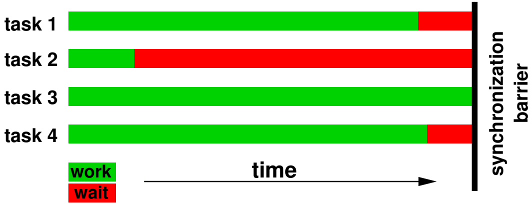
Loop Scheduling

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

- Loop is subdivided into as many chunks as threads exist.
- 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

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];
}
```

Eventually

Questions ?

Coffee

Practicals

Lunch