National Aeronautics and Space Administration

Advanced OpenMP Topics

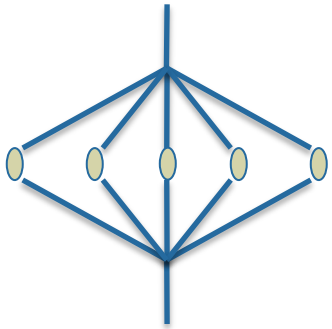
NAS Webinar

September 12, 2012

NASA Advanced Supercomputing Division

Outline

- The *fork-join* model (a refresh)
- Nested parallelism
- OpenMP tasking
  - Task execution model
  - Data scoping
  - Task synchronization
- Performance considerations
- Correctness issues
- Future OpenMP extensions



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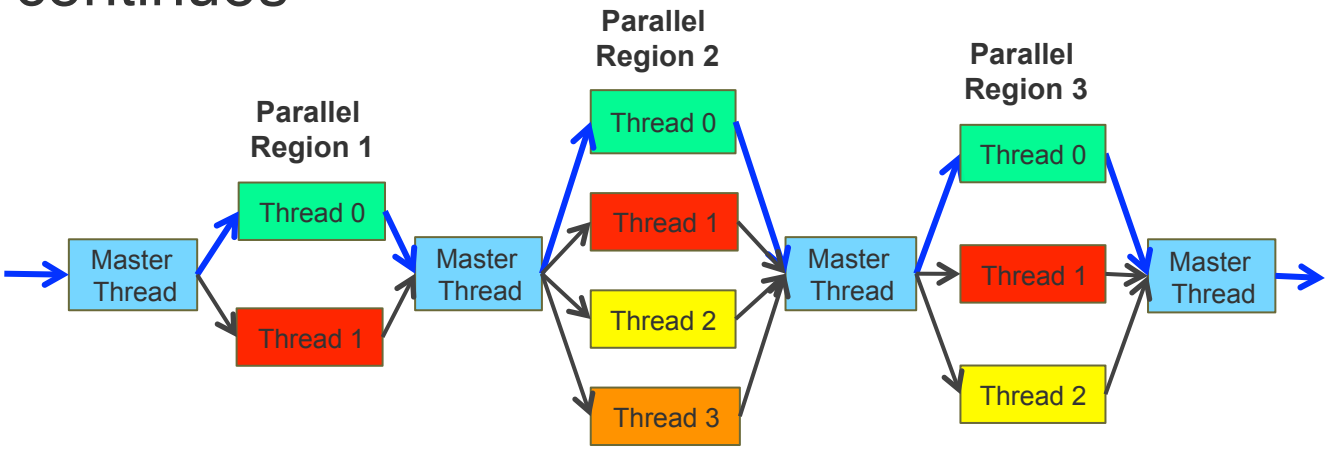
The *Fork-Join* Model

- Multiple threads are forked at a **parallel** construct
  - The *master* thread is part of the new thread team
- *Worksharing* constructs distribute work in the parallel region
  - **for** or **do, sections, single**
- Synchronization primitives synchronize threads
  - *barrier*, **critical**, *locks*
- Threads join at the end of the parallel region and the *master* thread continues



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Nested Parallelism

- Parallel regions can be nested inside another
  - Exploiting parallelism at multiple nesting levels since single level may not be enough

```
#pragma omp parallel for num_threads(2)
for (j=0; j<m; j++) {
  #pragma omp parallel for num_threads(3)
   for (i=0; i<n; i++) {
      c[j][i] = a[j][i] + b[j][i];
   }
}
```

First level parallel region with 2 threads

Second level parallel region with 3 threads for each outer thread with a total of 6 threads

- To enable nested parallel regions
  - **OMP_NESTED**=true or call **omp_set_nested**(1)
  - If not, the inner parallel region will be started with a team of one thread
- To set the number of threads
  - Call **omp_set_num_threads**() or use the ***num_threads*** clause
  - **OMP_NUM_THREADS**=2,3 (OpenMP 3.1)

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Nested Parallelism (cont.)

- Issues with nested parallel regions
  - Performance is a concern
    - Overhead from fork and join
    - Issue with data locality and data reuse
    - *Implicit barrier* at the end of each inner parallel region
  - Not all compilers (such as PGI compiler) provide the support
- The ***collapse*** clause for multiple loops (OpenMP 3.0)
  - Combines closely nested loops into one
  - More efficient than nested parallel regions

```
#pragma omp parallel for collapse(2)
for (j=0; j<m; j++) {
   for (i=0; i<n; i++) {
      c[j][i] = a[j][i] + b[j][i];
   }
}
```

Combines both i and j loops

Tasking in OpenMP

- Limitation of the fork-join model with worksharing constructs
  - Work units statically determined in worksharing constructs
    - No easy method to dynamically generate work units
  - Lack of support for recursive algorithms
    - For example, no easy way to traverse a tree in parallel
- Tasking model
  - Introduced in OpenMP 3.0
  - Complimentary to the thread-centric model
  - Ability to express parallelism for recursive algorithms, pointer chasing, which are commonly encountered in C/C++
  - Constructs for task generation and task synchronization
  - Concept of task switching

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Basic Task Concept

- OpenMP task
  - A code entity including control flow and its data environment, executed by a thread
- *Implicit* and *explicit tasks*
  - *Implicit tasks* generated via the **parallel** directive
  - *Explicit tasks* generated via the **task** directive
- Task synchronization
  - The **taskwait** directive to wait for all *child tasks* of the current task
  - Implicit or explicit barriers to wait for all *explicit tasks*
- Data environment is associated with tasks except for *threadprivate* storage
- Locks are owned by tasks
  - Set by a task, unset by the same task

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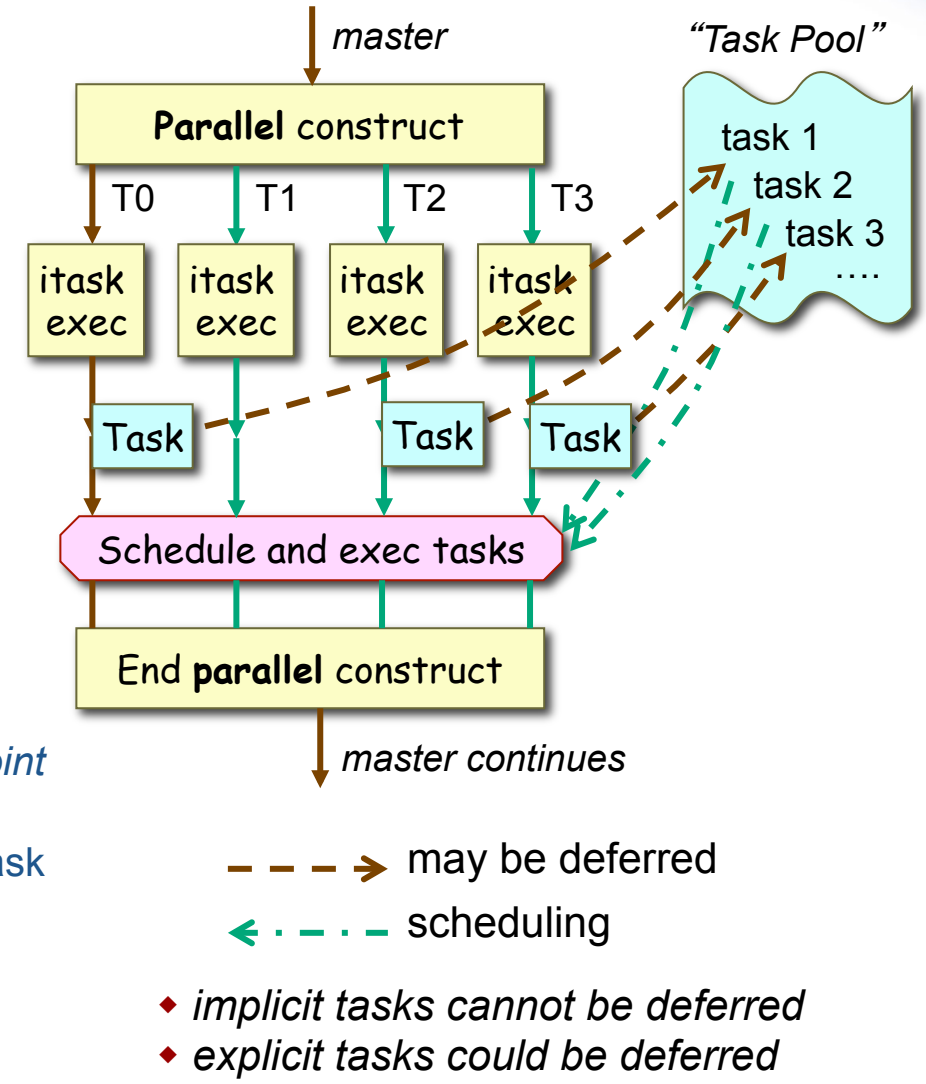
Task Execution Model

- Starts with the *master* thread
- Encounters a **parallel** construct
  - Creates a team of threads, *id 0* for the *master* thread
  - Generates implicit tasks, one per thread
  - Threads in the team executes implicit tasks
- Encounters a worksharing construct
  - Distributes work among threads (or implicit tasks)
- Encounters a **task** construct
  - Generates an explicit task
  - Execution of the task could be deferred
- Execution of explicit tasks
  - Threads execute tasks at a *task scheduling point* (such as **task**, **taskwait**, *barrier*)
  - Thread may switch from one task to another task
- At the end of a **parallel** construct
  - All tasks complete their execution
  - Only the *master* thread continues afterwards



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Thread versus Task

- Threading model
  - Thread and work (or task) go together
  - No concept of deferred execution
- Tasking model
  - Task generation and task execution are separate
  - There is no direct control on when a task gets executed
  - Thread is an execution engine
  - It is a more dynamic environment
- OpenMP supports both models

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Tasking Example: Fibonacci Number

```
int main()
{
  int res, n=45;
  #pragma omp parallel
  {
    #pragma omp single
     res = fib(n);
  }
  printf("fib(%d)=%d\n",
         n,res);
}
```

```
int fib(int n)
{
  int x, y;
  if (n < 2) return n;
   #pragma omp task shared(x)
    x = fib(n-1);
   #pragma omp task shared(y)
    y = fib(n-2);
   #pragma omp taskwait
  return(x+y);
}
```

Explicit tasks with proper data sharing attributes

Ensure calculations for x and y are done and storage does not disappear

Single thread generates tasks, but multiple threads execute tasks

The code builds a binary task tree. Parallelism comes from the execution of tasks on the leaf nodes.

But don't expect any performance from this version!

Data Sharing in Tasks

- Default sharing attribute rules
  - *Shared* for implicit tasks
  - For explicit tasks
    - If a variable is determined to be shared in the parellel region, default is *shared*
    - Otherwise, default is *firstprivate* (to avoid out-of-scope data access)
- Use data sharing clauses explicitly, in particular if you are not sure
  - ***shared***, ***private***, ***firstprivate***, etc.

```
node_t *node_head, *p;
int n = 40;
#pragma omp parallel private(p)
{
 #pragma omp master
 {
   p = node_head;
   while (p) {
      #pragma omp task
       process(p,n);
     p = p->next;
   }
 }
 #pragma omp taskwait
}
```

"p" is private and "n" is shared in the parallel region

"p" is firstprivate and "n" is shared for the task

Example of pointer chasing

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Common Problems in Using OpenMP

- Code is not scaling – possible issues:
  - Overhead of OpenMP constructs
  - Granularity of work units
  - Remote data access and NUMA effect
  - Load imbalance
  - False sharing of cache
  - Poor resource utilization
- Parallel code gives a slightly different result than the serial code
  - Understanding parallel reduction
- Code crashes or gives different results from run to run
  - Stack size limitation
  - Data race

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Overhead and Granularity

- Overhead from OpenMP constructs
  - Fork-join of threads
  - Barrier
  - Creation and scheduling of tasks
  - May be measured with the EPCC microbenchmarks
- Not enough granularity in work unit
- Possible solutions
  - Increase work and exploit parallelism at coarser level
  - Merge parallel regions if possible
  - Avoid barrier if possible (e.g., with ***nowait*** clause)
  - Use **atomic** over **critical** or **reduction**

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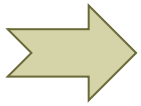
Reducing Overhead

Example 1

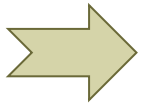
```
#pragma omp parallel for
  for (i=0, i<n; i++)
    a[i] = b[i] + c[i];

#pragma omp parallel for
  for (i=0; i<n; i++)
    d[i] = e[i] + f[i];
```



```
#pragma omp parallel
{ #pragma omp for nowait
    for (i=0; i<n; i++)
      a[i] = b[i] + c[i];
  #pragma omp for nowait
    for (i=0; i<n; i++)
      d[i] = e[i] + f[i];
}
```

Example 2

```
for (i=0; i<m; i++){
 #pragma omp parallel for
  for (j=0; j<n; j++)
    a[i][j] += a[i-1][j]
        + a[i+1][j];
}
```



```
#pragma omp parallel private(i)
for (i=0; i<m; i++){
  #pragma omp for
   for (j=0; j<n; j++)
     a[i][j] += a[i-1][j]
         + a[i+1][j];
}
```

- Merge parallel regions
- Use ***nowait*** if no data dependence between worksharing regions

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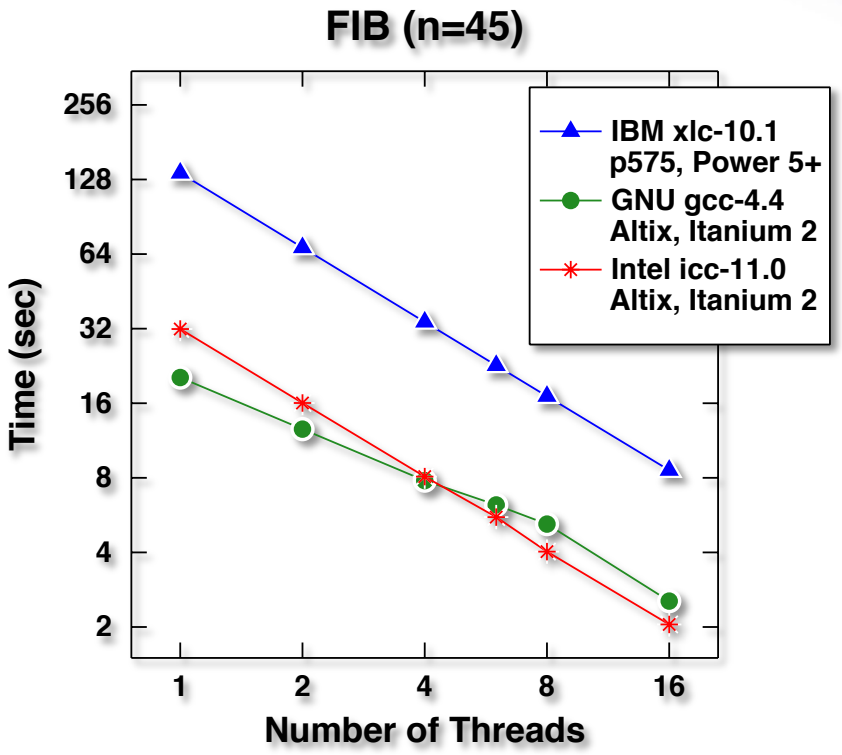
Fibonacci Number – Increased Granularity

```
int fib(int n)
{
  int x, y;
  if (n < 2) return n;
  if (n < 30)
    return (fib(n-1)+fib(n-2));
  #pragma omp task shared(x)
    x = fib(n-1);
  #pragma omp task shared(y)
    y = fib(n-2);
  #pragma omp taskwait
  return(x+y);
}
```

IF condition added to avoid fine-grained tasks and increase task granularity

Each task performs some amount of work!



Performance from the naïve version is not shown here – it is more than 10-fold worse and does not scale

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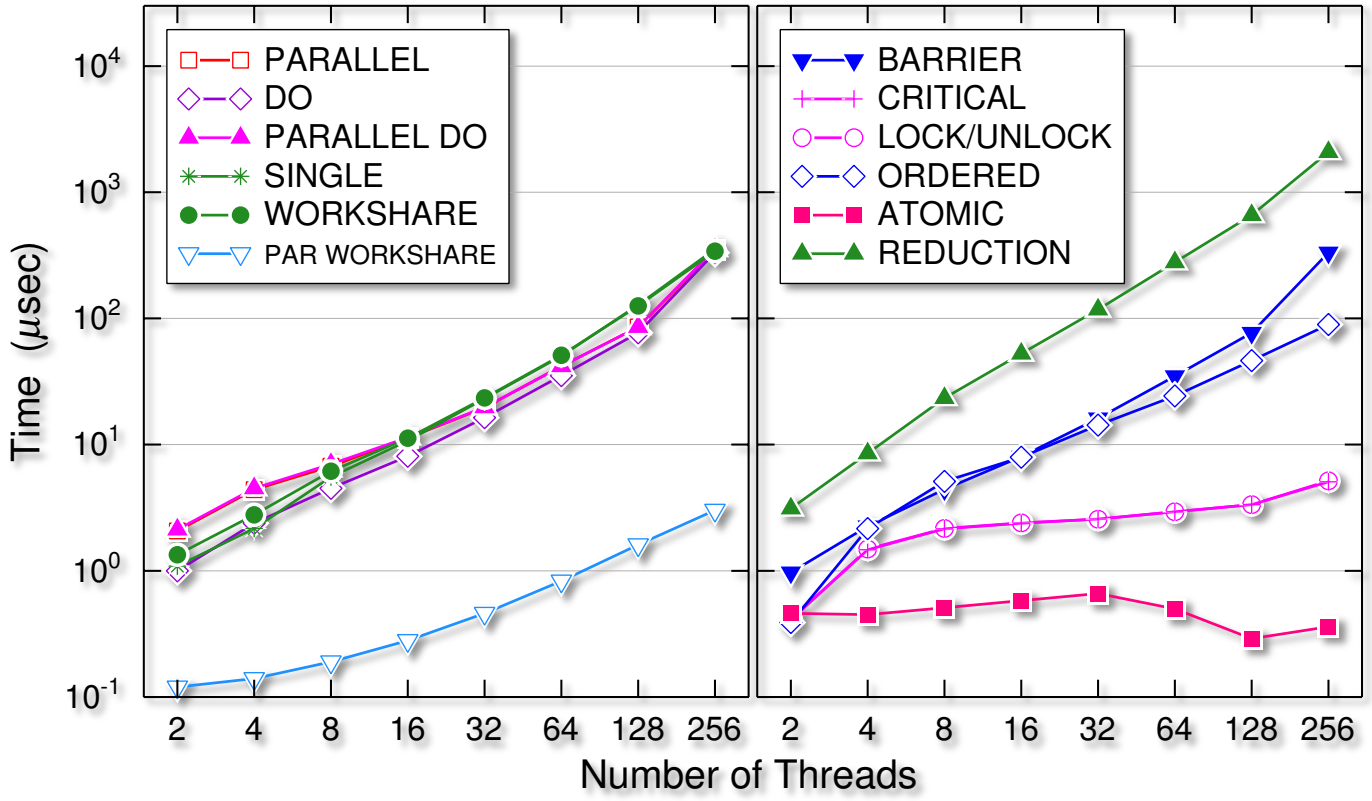
EPCC Microbenchmark Results



- Measure extra time spent (or overhead) by each OpenMP construct as a function of thread counts on the SGI Altix
- Intel OpenMP compiler was used
- Constructs such as **parallel**, **reduction**, **barrier** have very large overhead

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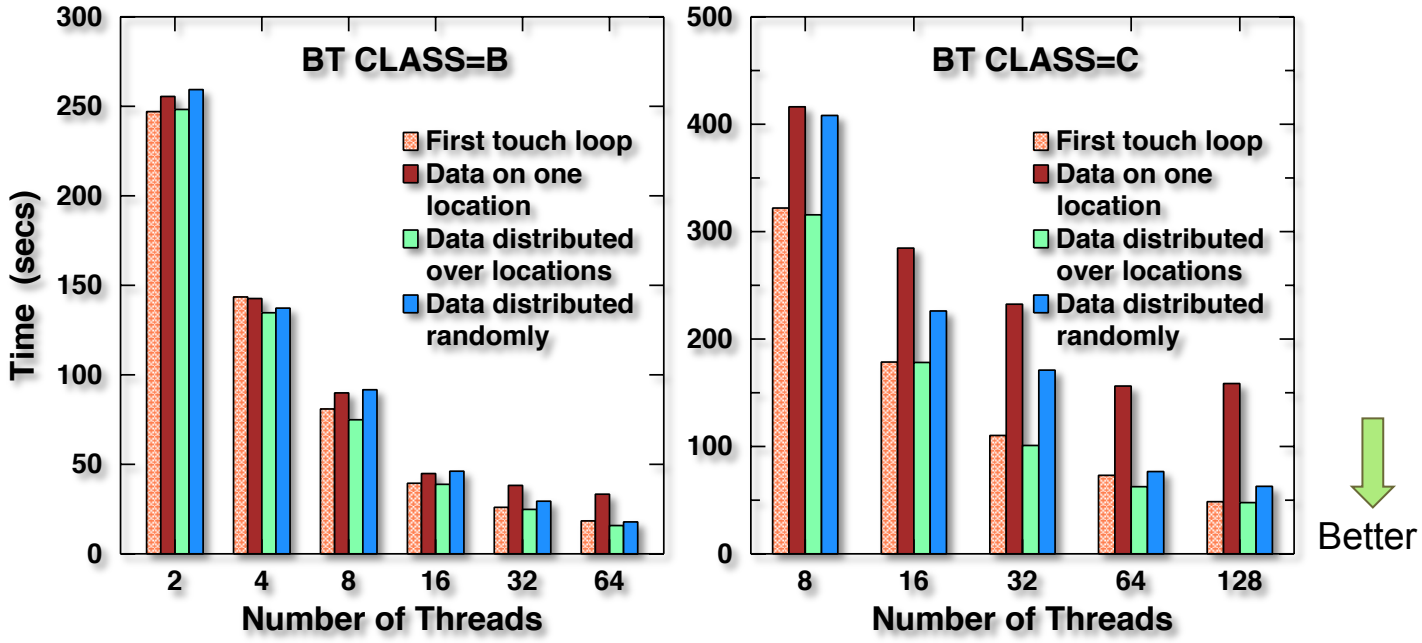
Remote Data Access and NUMA Effect

- Remote data access is more expensive
  - May cause memory access bottleneck
- Possible solutions
  - Use thread-local data (private or threadprivate) if possible
  - Add the *first touch* loop



- Performance of BT from the NAS Parallel Benchmarks on the SGI Altix
- Four types of data layout based on how data are initially distributed

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Other Performance Issues

- Load imbalance
  - Try the *dynamic* loop schedule
  - Increase iteration space by using the **`collapse`** clause for nested loops
- False sharing
  - Caused by multiple threads updating data in the same cache line
  - Work-around
    - Pad array dimension of shared data
    - Use private data if possible
- A good practice
  - Use **`omp_get_wtime()`** to get timing profile for code sections in question

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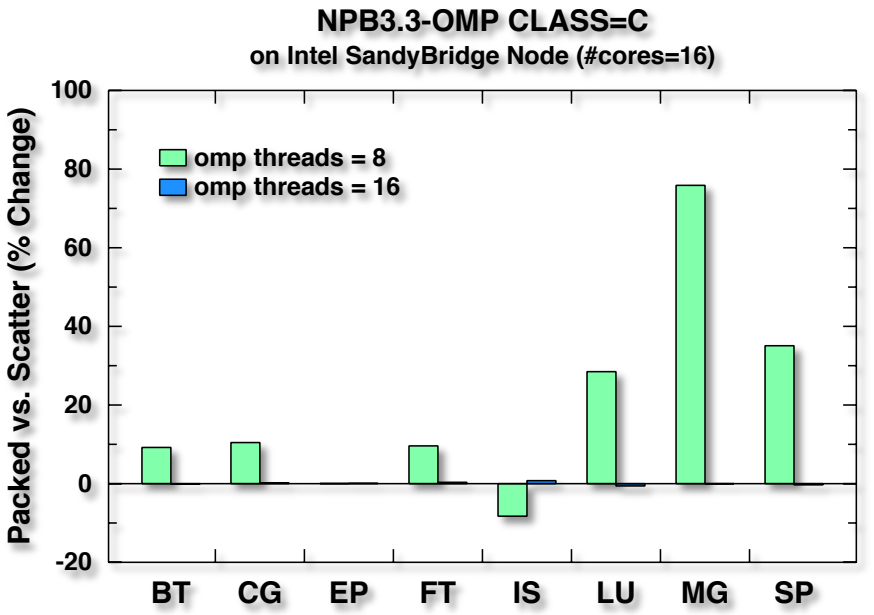
Thread-Processor Binding

- Or thread affinity
  - May improve performance by reducing OS scheduling overhead and improving resource utilization
  - Reduce run-to-run timing variation
  - But no standard way currently to control the affinity setting
    - For Intel compiler, set **`KMP_AFFINITY`**={scatter,compact..}

Example of using thread binding from two types of affinity settings to improve resource utilization



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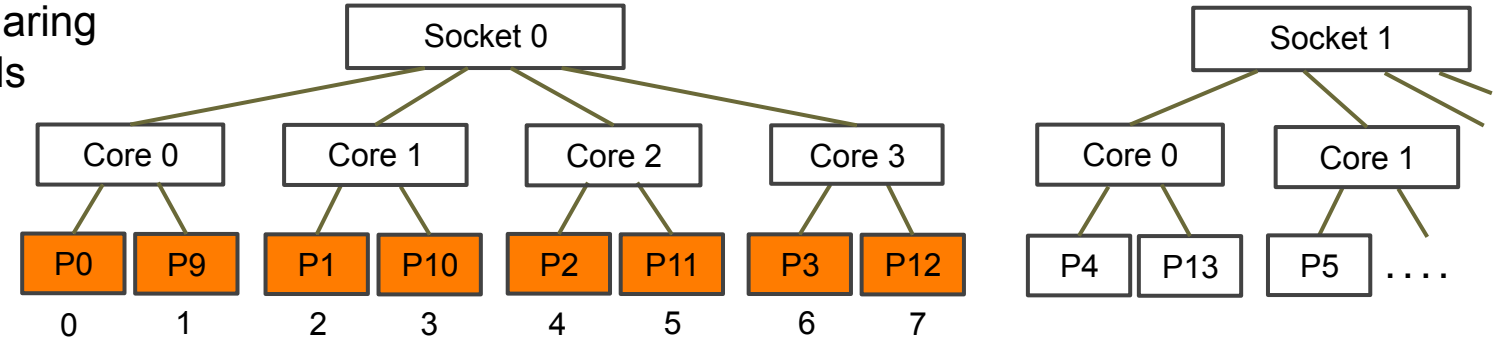
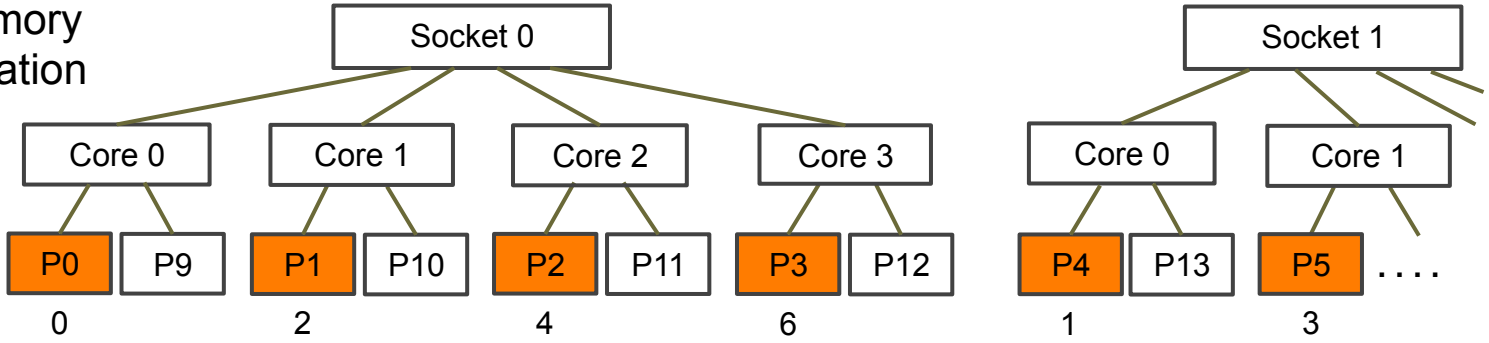
Thread Affinity Types

Examples of Intel Compiler, **OMP_NUM_THREADS=8**, two quad-core sockets

KMP_AFFINITY=*compact*
better cache sharing between threads



KMP_AFFINITY=*scatter*
maximizing memory bandwidth utilization



– *"scatter" usually gives better results for most cases*

KMP_AFFINITY=*explicit,proclist=[0-7]*
user specifies the proc list explicitly

For more details, see www.nas.nasa.gov/hecc/support/kb/60/

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Code Correctness Issues

- Parallel reduction
  - May not be bit reproducible as the serial result
  - Mathematically associative: (x + y) + z = x + (y + z), but machine accuracy is limited for floating point
  - Use double precision over single precision for reduction variables

- Some common programming errors
  - Incorrect variable scoping
  - Accessing reduced variable without a barrier
  - Master versus single
    - Master doesn't have a barrier, but single does
  - Race condition

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Race Condition

- Commonly encountered in shared memory programming
  - Results are not deterministic
  - Unintentional (programming error), intentional (one thread polling a flag that is updated by another thread)
- Occurs when all the following hold
  - Multiple threads access the same memory location concurrently
  - One of the access is write
  - Access is not protected (e.g., by critical construct)

Updating private variable "tid" is OK

Data race on "n"

```
#pragma omp parallel private(tid)
{
  tid = omp_get_thread_num();
  n = tid;
}
```

Updating shared variable "n" from multiple threads causes a race.
Race condition should be avoided by all means.

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Code Correctness Issues (cont.)

- Code crashes
  - Caused by programming errors
    - Debugging the code with a debugger (*gdb*, *totalview*, etc.)
  - Runtime stack size limitation
    - Default thread stack size can be easily exhausted
    - Reset stack size for master threads via shell command

      `limit stacksize unlimit` (csh)

      `ulimit -s unlimited` (sh)
    - Reset stack size for worker threads via environment variable

      `setenv OMP_STACKSIZE 12m` (csh)

      `export OMP_STACKSIZE=12m` (sh)

Software Tools

- Correctness checking
  - Variable scoping
    - "*Auto*" scoping supported by the Oracle OpenMP compiler
  - Race condition detection
    - Intel Thread Checker (or Parallel Inspector)
    - Oracle Thread Analyzer
- Performance tools
  - Compiler feedback
  - Profiling tools
    - ompP (UCB), PerfSuite (NCSA), Vtune (Intel), TAU (U.Oregon), etc.
- Parallelization assistant
  - Compiler auto-parallelization
  - Semi-automatic parallelization tools (CAPO/Parawise)

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Future OpenMP Extensions

- Work in progress within the OpenMP language committee
  - Public draft of the 4.0 specification by the end of the year
- New features under consideration
  - User-defined reduction
  - Error handling
    - The **cancel** construct for parallel and worksharing
    - *Cancellation* points
  - Fortran 2003 support
  - Thread affinity
    - Logical processor units via the **OMP_PLACES** environment variable
    - Affinity policy (***compact***, ***scatter***, ***master***) for threads in parallel regions
    - Handling thread affinity in nested parallel regions
  - **Atomic** construct for sequential consistency
    - **atomic *seq_cst***

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Support for Accelerator Devices

- Such as GPUs, Intel Xeon Phi (MIC)
  - Many cores, large amount of parallelism
  - Disjoint device memory from the host
- Programming models
  - Low level models (CUDA, OpenCL) exist, but hard to use
  - High level models are being developed
- OpenACC model (for GPUs)
  - Based on the PGI Accelerator programming model, defined by multi-vendors (www.openacc-standard.org)
  - Using compiler directives, as in OpenMP
  - Offloading work to the device
  - Data transfer between the host and the device
  - Intend to merge into OpenMP eventually

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Summary

- OpenMP provides a programming model for shared memory systems
- Compilers with OpenMP support are widely available
- The tasking model opens up opportunities for a wider range of applications
- Several issues to consider for developing efficient OpenMP codes
  - OpenMP overhead
  - Data locality
  - In some cases trade-off between easy of use and performance
    - With some extra effort, scalability can be achieved in many cases

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References

- OpenMP specifications
  - www.openmp.org/wp/openmp-specifications/
- Resources
  - www.openmp.org/wp/resources/
  - www.compunity.org/
- Benchmarks
  - OpenMP Microbenchmarks from EPCC (www.epcc.ed.ac.uk/research/openmpbench)
  - NAS Parallel Benchmarks (www.nas.nasa.gov/publications/npb.html)
- Porting applications to Pleiades
  - www.nas.nasa.gov/hecc/support/kb/52/
  - www.nas.nasa.gov/hecc/support/kb/60/

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