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
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

![Diagram of Fork-Join Model]

Question? Use the Webex chat facility to ask the Host
Nested Parallelism

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

```c
#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];
    }
}
```

- 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)
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

```c
#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
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
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

*Implicit tasks cannot be deferred*
*Explicit tasks could be deferred*
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
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);
}

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!

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
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 parallel 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
}
```

Example of pointer chasing

“p” is private and “n” is shared in the parallel region

“p” is firstprivate and “n” is shared for the task
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
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`
Reducing Overhead

Example 1

```c
#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];
```

Example 2

```c
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];
}
```

```c
#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

Question? Use the Webex chat facility to ask the Host
```c
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);
}
```

**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**
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
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
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
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 \texttt{KMP\_AFFINITY}={scatter,compact..}

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

![Graph showing performance comparison between packed and scatter thread binding with Intel compiler.](image)
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.nasa.gov/hecc/support/kb/60/
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
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)

```
#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.*
Code Correctness Issues (cont.)

• Code crashes
  – Caused by programming errors
    • Debugging the code with a debugger (\textit{gdb}, \textit{totalview}, etc.)
  – Runtime stack size limitation
    • Default thread stack size can be easily exhausted
    • Reset stack size for master threads via shell command
      \begin{verbatim}
      limit stacksize unlimit (csh)
      ulimit –s unlimited        (sh)
      \end{verbatim}
    • Reset stack size for worker threads via environment variable
      \begin{verbatim}
      setenv OMP_STACKSIZE 12m   (csh)
      export OMP_STACKSIZE=12m   (sh)
      \end{verbatim}
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)
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
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
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
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/