A Uniform Programming Model for Petascale Computing

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Agenda

- OpenMP 3.0
- Challenges in Scaling OpenMP
- Heterogeneous Systems / Nodes
The OpenMP Shared Memory API

- High-level directive-based multithreaded programming
  - The user makes strategic decisions
  - Compiler figures out details
  - Threads communicate by sharing variables
  - Synchronization to order accesses and prevent data conflicts
  - Structured programming to reduce likelihood of bugs

```
#pragma omp parallel
#pragma omp for schedule(dynamic)
for (I=0;I<N;I++){
    NEAT_STUFF(I);
} /* implicit barrier here */
```

The OpenMP ARB

- OpenMP is maintained by the OpenMP Architecture Review Board (the ARB), which
  - Interprets OpenMP
  - Writes new specifications - keeps OpenMP relevant
  - Works to increase the impact of OpenMP

- Members are organizations - not individuals
  - Current members
    - Permanent: AMD, Cray, Fujitsu, HP, IBM, Intel, Microsoft, NEC, PGI, SGI, Sun
    - Auxiliary: ASCI, cOMPunity, EPCC, KSL, NASA, RWTH Aachen

www.openmp.org
www.compunity.org
OpenMP 3.0 Introduces Tasks

- Tasks explicitly created and processed
  - Each encountering thread packages a new instance of a task (code and data)
  - Some thread in the team executes the task

```c
#pragma omp parallel
{
    #pragma omp single
    {
        p = listhead;
        while (p)
        {
            #pragma omp task
            process (p)
            p=next (p);
        }
    }
}
```

Synchronization provided by `#pragma omp taskwait`

Nested Parallelism in OpenMP 3.0

- Per-thread internal control variables
  - Allows, for example, calling `omp_set_num_threads()` inside a parallel region.
  - Controls the team sizes for next level of parallelism
  - Different regions may have different defaults
- Library routines to determine depth of nesting, parent IDs, their team sizes etc.
  - `omp_get_active_level()`
  - `omp_get_ancestor(level)`
  - `omp_get_teamsize(level)`

Version 3.0 ratified by ARB May 2008
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Multicore Is Everywhere

- Small, but growing, number of cores sharing memory
- Individual core may run one or more threads
- Some resources shared between threads (L2 cache, memory bandwidth): details depend on specific architecture
- Introduces need to consider scalability of API and implementation
Subteams of Threads?

Thread Subteam: original thread team is divided into several subteams, each of which can work simultaneously. Topologies could also be defined.

- Rather like MPI’s groups of pre-existing processes and operations among groups
- Worksharing among groups of pre-existing threads (i.e. a subset of current team of threads)

Increases expressivity of single-level parallelism
OpenMP Locality: Thread Subteams

```
for (j=0; j<ProcessingNum; j++) {
    #pragma omp for on threads (m:n:k )
    for k=0; k<M; k++) {
        // on threads in subteam
        Process_data ();
    }                          // barrier involves subteam only
```

- Flexible code region/worksharing/synchronization extension
- Low overhead because of static partition
- Facilitates thread-core mapping for better data locality and less resource contention
- Supports heterogeneity, **hybrid programming**, composition

**BT-MZ Performance with Subteams**

Platform: Columbia@NASA

Subteam: subset of existing team
Cart3D OpenMP Scaling

4.7 M cell mesh Space Shuttle Launch Vehicle example

- OpenMP version uses same domain decomposition strategy as MPI for data locality, avoiding false sharing and fine-grained remote data access
- OpenMP version slightly outperforms MPI version on SGI Altix 3700BX2, both close to linear scaling.

Locality, Locality, Locality

- OpenMP does not permit explicit control over data locality
- Thread fetches data it needs into local cache
- Implicit means of data layout popular on NUMA systems
  - As introduced by SGI for Origin
  - “First touch”
- Emphasis on privatizing data wherever possible, and optimizing code for cache
  - This can work pretty well
  - But small mistakes may be costly
Ideas for Locality Support

- Control thread placement as well as data locality
- Data placement techniques:
  - Rely on implicit first touch or other system support
  - Possibly optimize e.g. via preprocessing step
  - Provide a “next touch” directive that would store data so that it is local to next thread accessing it
- Thread binding techniques:
  - Do this via system calls, command line
  - Programmer hints to “spread out”, “keep close together
  - Logical machine description?
  - Logical thread structure?
- HPF-like data placement directives

“Places” to Enhance Data Locality?

- The place concept is introduced in X10
  - A logical region in the system that data and threads may have affinity with
  - Mapping to hardware nodes at runtime
  - Possible to allocate data within a place
- Could add places to OpenMP
  - Associate worksharing constructs with a place
  - Could permit additional kind of shared memory

#pragma omp task OnPlace(place)
Example: Nested Parallelism and Places

```c
#pragma omp place (N) // N is number of places
#pragma omp parallel num_threads(N) OnPlace(All)
{
    int MyPlace = omp_get_place_num();
    #pragma omp parallel OnPlace(MyPlace)
    ...
    Omp parallel OnPlace(All)
}
```

Data Attributes Within a Place

- “Place-shared” variable: a variable shared only within threads in a place

- Default is place-shared if parallel region is associated with a single place
Synchronization Matters

- Reliance on global barriers, critical regions and locks
- Critical region is very expensive
  - High overheads to protect often just a few memory accesses
- It’s hard to get locks right
  - And they may also incur performance problems

- Point-to-point synchronization could reduce overall waits
- Condition variables might enable finer-grain synchronization
- Transactions might be an interesting addition
  - Most likely at implementation level only
  - Especially if hardware support provided

Offending critical region was rewritten

Courtesy of R. Morgan, NASA Ames
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**A Heterogeneous World**

- Heterogeneous programming is currently very low-level
  - How are we going to program such systems in future?
  - If OpenMP is to be used to program a board with devices such as accelerators, GPGUs, extensions are needed

- How to identify code that should be moved to accelerators?
- How to share data between host cores and other devices?
- How is this compiled?
- Debugged?
ClearSpeed Accelerator: CSX 600 designed for HPC

- **Processor Core:**
  - 40.32 64-bit GFLOPS
  - 10W typical
  - 210MHz
  - 96 PEs, 6 Kbytes each
  - 8 redundant PEs

- **SoC details:**
  - integrated DDR2 memory controller with ECC support
  - 128 Kbytes of SRAM

- **Design details:**
  - IBM 130nm process
  - 128 million transistors (47% logic, 68% memory)

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**Streaming**

- Create streams for moving data in and out of a special device or a place
  - Program is directed graph of tasks and streams
  - Popular for programming embedded systems
  - Needs to be supported in model for heterogeneous systems
  - But also corresponds to structure of some high-end applications
  - Implementation needs to take care of data motion to/from limited device memories
How to Express Streaming?

```c
#pragma omp CreateStreams s1(a), s2(b), s3(c)
#pragma omp task in(s1) out(s2)
    converter(s1, s2);
#pragma omp task in(s2) out(s3)
    compression(s2, s3);
```

Create streams and associate them with data.

Link streams with tasks/worksharing to define input and output streams.

The pair of tasks will be executed in pipelined fashion.

Alternative: have in/out clauses associated with parallel regions. The variables may be passed via point-to-point synchronization constructs.

Example: Heterogeneous Extensions

- PGI has introduced OpenMP-like directives
  - To specify regions whose loops will be compiled for acceleration as far as possible
  - User may specify device, input and output data, portions for sequential execution, unrolling, SIMD..
  - Compiler attempts to translate for target device

```c
#pragma omp task parallel for (int i=0; i<N; i++)
#pragma omp task parallel for SIMD(32) // inner level parallelism
for (int j=0; j<N; j++)
    a[i,j] = b[i][j] * c[i][j]
```
Example: CAPS HMPP

- Declare hardware specific implementations of functions (HMPP codelets)
  - Can be specialized to the execution context (data size, ...)

- Codelet calls (RPC)
  - Synchronous, asynchronous properties

- Data transfers
  - Data prefetching

- Synchronization barriers
  - Host CPU will wait until remote computation is complete

CAPS: Multiple Devices

- Use #D accelerators in parallel

```c
#pragma omp parallel for, private (j)
for (jj=0; jj<#D; jj++)
  for (j=jj*(n/#D); j<jj*(n/#D)+(n/#D); j++)
    #pragma hmpp tospeedup1 callsite
    simplefunc1(n, t1[j], t2, t3[j], alpha);
#pragma hmpp tospeedup1 release
```
Heterogeneous Large-Scale Systems?

- Parallel region across machine, needs way to specify mapping of shared data at this level
- Inner level of parallel regions, mapped to places by application developer
  - Shared data is at same place
- In/out clauses to specify data that may be transferred between regions
- Additional levels of parallel regions to map code to accelerators, also with in/out clauses

Summary

- OpenMP needs extensions if it is to be a useful high-end programming model
- Locality support is essential
- Heterogeneity is present in high-end, general-purpose and embedded systems
- To support heterogeneity, OpenMP also needs some extensions
- Placement of code, more data locality support
- Compiler technology needs to be developed