User-Level Threads and OpenMP

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Top500 Supercomputers Today

1. Sunway TaihuLight (Sunway MPP): 10,646,600 cores
2. Tianhe-2 (Intel Xeon + Xeon Phi): 3,120,000 cores
3. Titan (Cray XK7 + Nvidia K20x): 560,640 cores
4. Sequoia (BlueGene/Q): 1,572,864 cores
5. K computer (SPARC64): 705,024 cores
6. Mira (BlueGene/Q): 786,432 cores

Number of cores per socket in Top500

Total number of cores in Top500 rank #1
Massive On-node Parallelism

- To address massive on-node parallelism, the number of work units (e.g., threads) must increase by 100X
- MPI+OpenMP is sufficient for many apps, but implementation is poor
  - Today MPI+OpenMP == MPI+Pthreads
- Pthread abstraction is too generic, not suitable for HPC
  - Lack of fine-grained scheduling, memory management, network management, signaling, etc.
- Better runtime can significantly improve MPI+OpenMP performance and support other emerging programming models
Outline

• Motivation
• User-Level Threads (ULTs)
• Argobots
• BOLT: OpenMP over Lightweight Threads
• Summary
User-Level Threads (ULTs)

- What is user-level thread (ULT)?
  - Provides thread semantics in user space
  - Execution model: **cooperative timesharing**
    - More than one ULT can be mapped to a single kernel thread
    - ULTs on the same OS thread do not execute in parallel
  - Can be implemented with coroutines
    - Enable explicit suspend and resume of its progress by preserving execution state
    - Some languages such as Python and Go use coroutines for asynchronous I/O

ULTs:

Kernel threads:
User-Level Threads (ULTs)

• Why ULTs?
  – Conventional threads (e.g., Pthreads) are too expensive to express massive parallelism
  – If we create Pthreads more than # of cores (i.e., oversubscription):
    • Context-switch and synchronization overhead will increase dramatically
  – ULTs can mitigate high overhead of Pthreads but need explicit control

• Where to use?
  – To better overlap computation and communication/IO
    • Low context-switching overhead of ULTs can give more opportunities to hide communication/IO latency
  – To exploit fine-grained task parallelism
    • Lightweight ULTs are more suitable to express massive task parallelism
Pthreads vs. ULTs

- Average time for creating and joining one thread
  - Pthread: 6.6us - 21.2us (avg. 34,953 cycles)
  - ULT (Argobots): 78ns - 130ns (avg. 191 cycles)
  - ULT is 64x - 233x faster than Pthread

- How fast is ULT?
  - L1$ access: 1.112ns, L2$ access: 5.648ns, memory access: 18.4ns
  - Context switch (2 processes): 1.64us

* measured using LMbench3
Growing Interests in ULTs

- ULT and task libraries
  - Converse threads, Qthreads, MassiveThreads, Nanos++, Maestro, GnuPth, StackThreads/MP, Protothreads, Capriccio, StateThreads, TiNy-threads, etc.
- OS supports
  - Windows fibers, Solaris threads
- Language and programming models
  - Cilk, OpenMP task, C++11 task, C++17 coroutine proposal, Stackless Python, Go coroutines, etc.

- Pros
  - Easy to use with Pthreads-like interface
- Cons
  - Runtime tries to do something smart (e.g., work-stealing)
  - This may conflict with the characteristics and demands of applications
Argobots

**Overview**
- Separation of mechanisms and policies
- Massive parallelism
  - **Exec. Streams** guarantee progress
  - **Work Units** execute to completion
    - User-level threads (ULTs) vs. Tasklets
- Clearly defined memory semantics
  - Consistency domains
    - Provide Eventual Consistency
  - Software can manage consistency

**Argobots Innovations**
- **Enabling technology, but not a policy maker**
  - High-level languages/libraries such as OpenMP or Charm++ have more information about the user application (data locality, dependencies)
- **Explicit model**: Enables dynamism, but always managed by high-level systems

*Current team members: Pavan Balaji, Sangmin Seo, Halim Amer (ANL), L. Kale, Nitin Bhat (UIUC)*
Argobots Execution Model

- **Execution Streams (ES)**
  - Sequential instruction stream
    - Can consist of one or more work units
  - Mapped efficiently to a hardware resource
  - Implicitly managed progress semantics
    - One blocked ES cannot block other ESs

- **User-level Threads (ULTs)**
  - Independent execution units in user space
  - Associated with an ES when running
  - Yieldable and migratable
  - Can make blocking calls

- **Tasklets**
  - Atomic units of work
  - Asynchronous completion via notifications
  - Not yieldable, migratable before execution
  - Cannot make blocking calls

- **Scheduler**
  - Stackable scheduler with pluggable strategies

- **Synchronization primitives**
  - Mutex, condition variable, barrier, future

- **Events**
  - Communication triggers
Explicit Mapping ULT/Tasklet to ES

- The user needs to map work units to ESs
- No smart scheduling, no work-stealing unless the user wants to use

Benefits
- Allow locality optimization
  - Execute work units on the same ES
- No expensive lock is needed between ULTs on the same ES
  - They do not run in parallel
  - A flag is enough
Stackable Scheduler with Pluggable Strategies

- Associated with an ES
- Can handle ULTs and tasklets
- *Can handle schedulers*
  - Allows to stack schedulers hierarchically
- Can handle asynchronous events
- *Users can write schedulers*
  - Provides **mechanisms**, not policies
  - Replace the default scheduler
    - E.g., FIFO, LIFO, Priority Queue, etc.
- ULT can explicitly **yield to** another ULT
  - Avoid scheduler overhead

```
yield()
yield_to(target)
```
Performance: Create/Join Time

• Ideal scalability
  – If the ULT runtime is perfectly scalable, the time should be the same regardless of the number of ESs

![Graph showing create/join time per ULT (cycles) with different execution streams and tools like Qthreads, MassiveThreads, Argobots (ULT), and Argobots (Tasklet).](image-url)
Argobots’ Position

Applications

High-Level Programming Models/Libraries
Domain Specific Languages (DSLs)

Argobots
Comm. Lib.

Node OS

Argobots
Comm. Lib.

Node OS

Argobots is a low-level threading/tasking runtime!
Argobots Ecosystem

MPI+Argobots

Charm++

Applications
Charm++
Argobots runtime
Communication libraries

OmpSs

CilkBots

Fused ULT N
Fused ULT 2
Fused ULT 1
RWS ULT

Argobots ES

Cilk “Worker”

PaRSEC

MPI

Argobots runtime

Sched

ES₁

... 

ESₙ

Argobots

OpenMP

More Connections

TASCEL, XMP, ROSE, GridFTP, Kokkos, RAJA, etc.

Origin

Mercury RPC

Target
OpenMP

- Directive based programming model
- Commonly used for shared-memory programming in a node
- Many different implementations
  - Typically on top of Pthreads library
  - Intel, GCC, Clang, IBM, etc.

**Sequential code**

```c
for (i = 0; i < N; i++) {
    do_something();
}
```

**OpenMP code**

```c
#pragma omp parallel for
for (i = 0; i < N; i++) {
    do_something();
}
```
int in[1000][1000], out[1000][1000];

#pragma omp parallel for
for (i = 0; i < 1000; i++) {
    lib_compute(i);
}

lib_compute(int x)
{
    #pragma omp parallel for
    for (j = 0; j < 1000; j++)
        out[x][j] = compute(in[x][j]);
}
Nested Parallel Loop: Implementations

- **GCC**
  - Does not reuse the idle threads in nested parallel constructs
  - All thread teams inside a parallel region need to be created
- **ICC**
  - Reuse idle threads
    - If there are not more threads available, new threads are created
- *All created threads are OS threads and add overhead*

- **Implementation using Argobots**
  - Creates ULTs or tasklets for both outer loop and inner loop

One ES for each core

Work unit for the outer loop

Outer loop synchronization point

Inner loop synchronization point

Each work unit executes a portion of the inner loop
Nested Parallel Loop: Performance

Execution time for 36 threads in the outer loop

GCC OpenMP implementation does not reuse idle threads in nested parallel regions, all the teams of threads need to be created in each iteration.

Some overhead is added by creating ULTs instead of tasks.
Nested Parallel Loop: Analysis

- How does each implementation manage the threads in nested parallel regions?

  - Parameters:
    - C: number of cores (or threads created by user at the beginning)
    - N: number of iterations of the outer loop
    - M: number of iterations of the inner loop
    - T: number of threads for the inner loop

Example -> C: 36, N: 1,000, M: 1,000, T:36

<table>
<thead>
<tr>
<th>Iple.</th>
<th># Created Threads</th>
<th># Reused Threads</th>
<th># Created ULTs</th>
<th># Created Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCC</td>
<td>C + N*(T-1) = 35,036</td>
<td>0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>ICC</td>
<td>C + C*(T-1) = 1,296</td>
<td>(N-C)*(T-1) = 33,740</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Argobots tasks</td>
<td>C = 36</td>
<td>0</td>
<td>C = 36</td>
<td>N*T = 36,000</td>
</tr>
</tbody>
</table>

Sequential creation  Parallel creation

 GCC
 ICC
 Argobots tasks

Example - C: 36, N: 1,000, M: 1,000, T:36

C + N*(T-1) = 35,036
C + C*(T-1) = 1,296
C = 36
N*T = 36,000
BOLT: A Lightning-Fast OpenMP Implementation

• About BOLT
  – BOLT is a recursive acronym that stands for "BOLT is OpenMP over Lightweight Threads"
  – https://www.mcs.anl.gov/bolt/

• Objective
  – OpenMP framework that exploits *lightweight threads and tasks*

- Improved Nested Massive Parallelism
- Enhanced Fine-Grained Task Parallelism
- Better Interoperability with MPI and Other Internode Programming Models
Approach & Development

• Basic approach
  – Compiler simply generates runtime API calls, while the runtime creates ULTs/tasklets and manages them over a fixed set of computational resources
  – Use **Argobots** as the underlying threading and tasking mechanism
  – ABI compatibility with Intel OpenMP compilers, LLVM/Clang, and GCC (i.e., can be used with these compilers)

• Development
  – Runtime
    • Based on Intel OpenMP Runtime API
    • Generates Argobots work units from OpenMP pragmas
    • Can generate ULTs or tasklets depending on code characteristics
  – Compiler (planned)
    • LLVM/Clang
    • Passes characteristics of parallel region or task (e.g., existence of blocking calls) to the runtime
    • Extends pragmas with the option “nonblocking”
BOLT Execution Model

- OpenMP threads and tasks are translated into Argobots work units (i.e., ULTs and tasklets)
- Shared pools are utilized to handle nested parallelism
- A customized Argobots scheduler manages scheduling of work units across execution streams
Prototype Implementation of BOLT Runtime

• Based on Intel’s open-source OpenMP runtime
  – http://openmp.llvm.org/
• Kept the original runtime API for the ABI compatibility
• Designed and implemented the threading layer using Argobots and modified the runtime internal layer
OpenMP Pragma Translation

1. A set of $N$ threads is created at run time
   - If they have not been created yet
   - Commonly as many as the number of CPU cores
2. The number of iterations is divided between all the threads
3. A synchronization point is added after the for loop
   - Implicit barrier at the end of parallel for

```c
#pragma omp parallel for (1,2)
for (i = 0; i < N; i++) {
    do_something();
}
(3)
```
OpenMP Compiler & BOLT Runtime

```c
#pragma omp parallel

Clang and Intel compiler

__kmpc_fork_call(...){
    __kmp_fork_call(...)
    __kmp_join_call(...)
}
```

Intel OpenMP Runtime API

BOLT runtime

- Create Execution Streams (if needed)
- Add a ULT or tasklet to each ES
- Launch the work

- Join work units created
parallel for

```c
#pragma omp parallel for
for (i = 0; i < N; i++) {
    do_something();
}
```

Creates threads
Divides all iterations among threads
Synchronization point

Implementation using Argobots

One Execution Stream for each CPU core (or hardware thread)

```
ES 0
WU
S

ES 1
WU
S

...

ES K
WU
S
```

Each work unit executes a portion of the for loop

A synchronization point is added
## OpenUH OpenMP Validation Suite 3.1

<table>
<thead>
<tr>
<th></th>
<th>GCC 6.1</th>
<th>ICC 17.0.0 + Intel OpenMP</th>
<th>ICC 17.0.0 + BOLT runtime (Argobots)</th>
<th>BOLT (clang + Argobots)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of tested OpenMP constructs</td>
<td>62</td>
<td>62</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td># of used tests</td>
<td>123</td>
<td>123</td>
<td>123</td>
<td>123</td>
</tr>
<tr>
<td># of successful tests</td>
<td>118</td>
<td>118</td>
<td>122</td>
<td>112</td>
</tr>
<tr>
<td># of failed tests</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pass rate (%)</td>
<td>95.9</td>
<td>95.9</td>
<td>99.2</td>
<td>99.2</td>
</tr>
</tbody>
</table>

- The BOLT prototype functionally works well!
Nested Parallel Loop Microbenchmark

* The number of threads for the outer loop was fixed at 36.
Application Study: KIFMM

- Kernel-Independent Fast Multipole Method (KIFMM)
  - Offload dgemv operations to Intel MKL
- Evaluated the efficiency of the nested parallelism support in Intel OpenMP and BOLT during the Downward stage
  - 9 threads for the application (outer parallel region)
Application Study: ACME mini-app

- ACME (Accelerated Climate Modeling for Energy)
  - Implementing additional levels of parallelism through OpenMP nested parallel loops for upcoming many-core machines
- Preliminary results of testing the transport_se mini-app version of HOMME (ACME’s CAM-SE dycore)

![Normalized Execution Time Graph]

**ACME mini-app (transport_se)**

- Lower is better (up to 3.16x faster)
- oversubscription
Summary

- Massive on-node parallelism is inevitable
  - Need runtime systems utilizing such parallelism
- User-level threads (ULTs)
  - Lightweight threads more suitable for fine-grained dynamic parallelism and computation-communication overlap
- Argobots
  - A lightweight low-level threading/tasking framework
  - Provides efficient mechanisms, not policies, to users (library developers or compilers)
    - They can build their own solutions
- BOLT: OpenMP over Lightweight Threads
  - More efficient support of nested parallelism with Argobots ULTs and tasklets
  - Preliminary results show that BOLT is promising
Argo Concurrency Team

- Argonne National Laboratory (ANL)
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  - Abdelhalim Amer
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    • Jesus Labarta
  – RIKEN
    • Jinpil Lee
    • Mitsuhisa Sato
Try Argobots & BOLT

- **Argobots**
  - http://www.mcs.anl.gov/argobots/
  - git repository
    - https://github.com/pmodels/argobots
  - Wiki
    - https://github.com/pmodels/argobots/wiki
  - Doxygen

- **BOLT**
  - http://www.mcs.anl.gov/bolt/
  - git repository
    - https://github.com/pmodels/bolt-runtime
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Infrastructure Providers
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Q&A

• Thank you for your attention!

Questions?