Argonne NATIONAL LABORATORY

Argobots and its Application to Charm++

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U.S. DEPARTMENT OF ENERGY

Argo Concurrency Team

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  - Abdelhalim Amer
  - Marc Snir
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- University of Illinois at Urbana-Champaign (UIUC)
  - Laxmikant Kale (co-lead)
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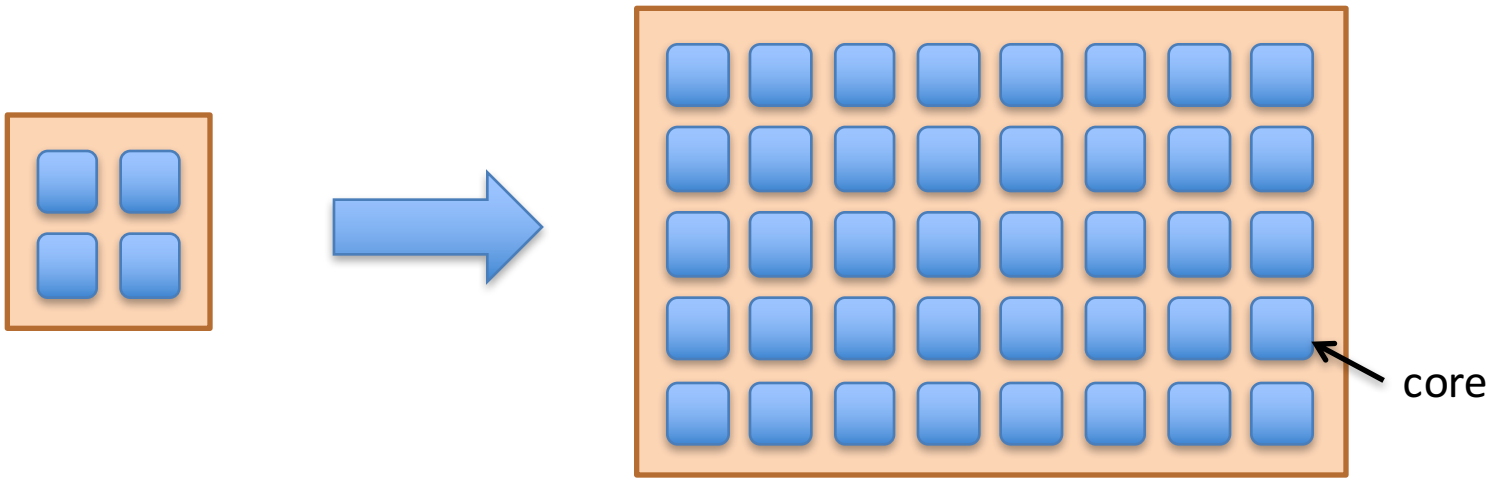
Massive On-node Parallelism

- The number of cores is increasing
- Massive on-node parallelism is inevitable
- Existing solutions do not effectively deal with such parallelism with respect to on-node threading/tasking systems or with respect to off-node communication in the presence of such tasks/threads
- *How to exploit?*



Core-level Parallelism

Shortcomings today? Pthreads (1/2)

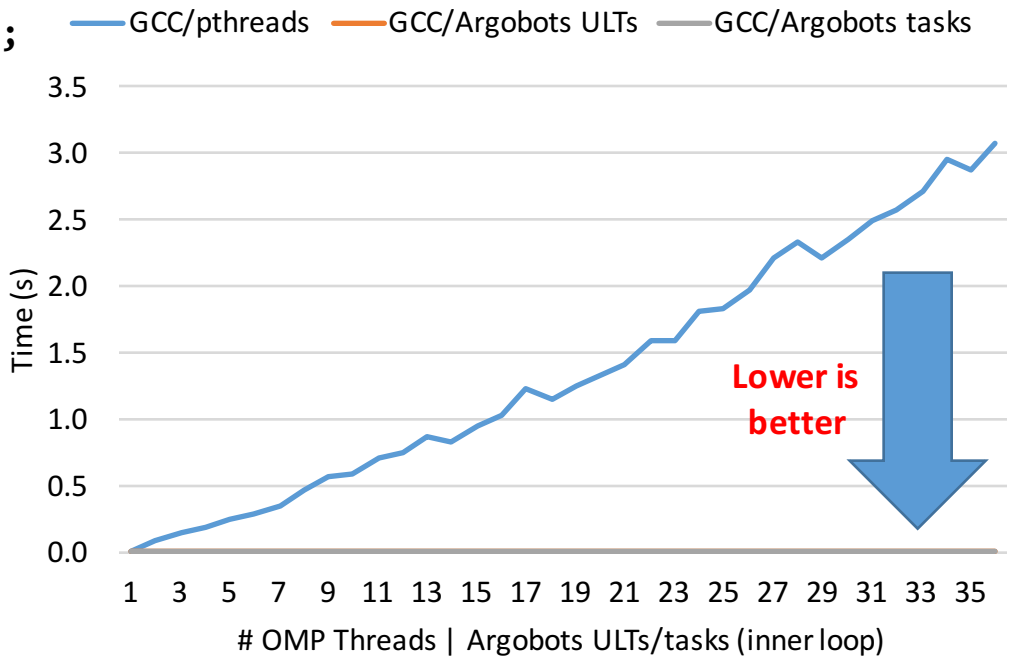
Nesting

```
int in[1000][1000], out[1000][1000];

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

petsc_voodoo(int x)
{
   #pragma omp parallel for
   for (j = 0; j < 1000; j++)
      out[x][j] = cosine(in[x][j]);
}
```

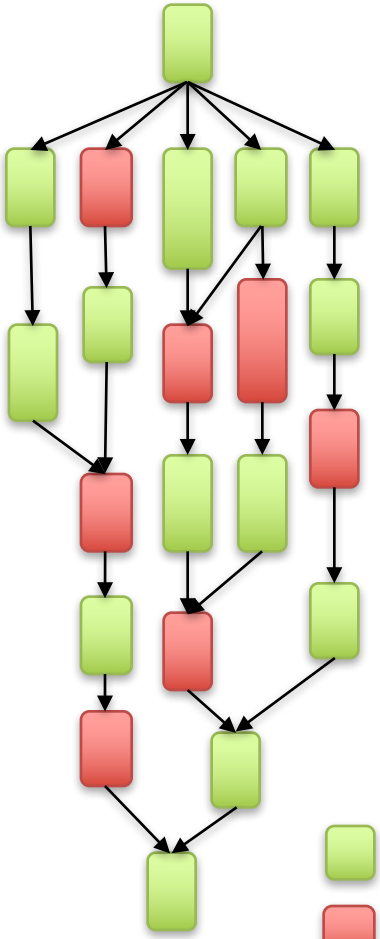
Execution time for 36 threads in the outer loop

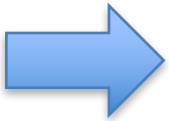


Why is traditional OpenMP's performance so bad? The compiler cannot analyze petsc_voodoo to know whether the function might ever block or yield, so it has to assume that it might. Therefore a stack is needed to facilitate it. Creating additional Pthreads for each nesting is the simplest way to achieve this.

Shortcomings today? Pthreads (2/2)

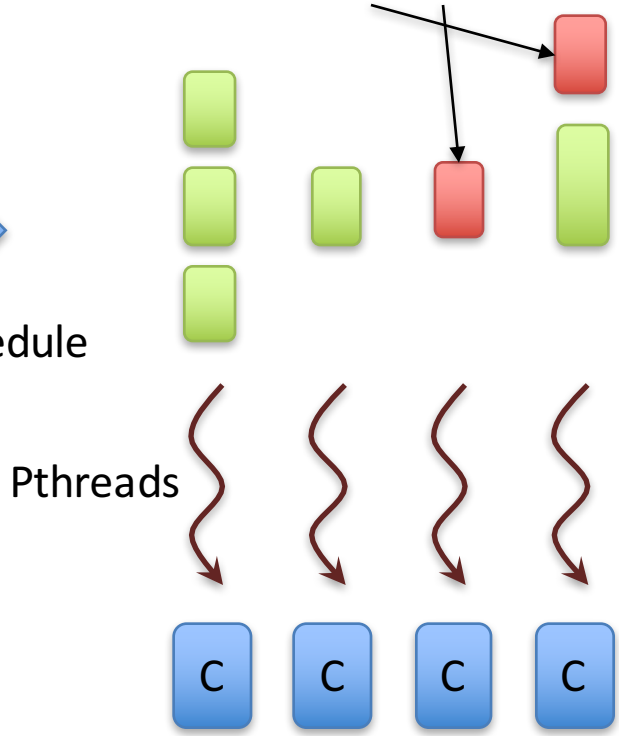
Tasks of application mapped to a group of Pthreads



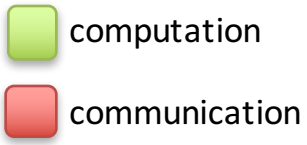


map & schedule

How about these communications?
Wait or context switch?



Work units intermixed with blocking calls (such as communication calls) can cause idle cores



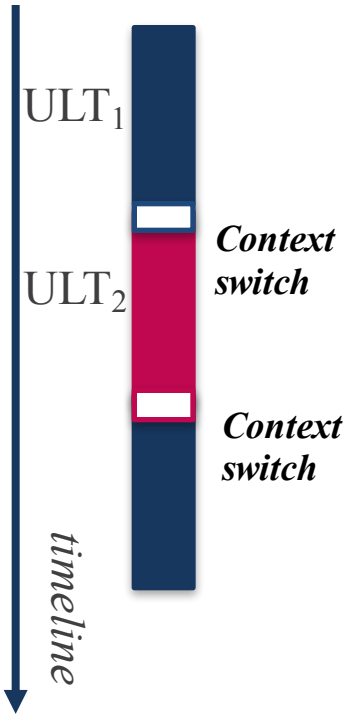
Need lightweight mechanisms to switch tasks!

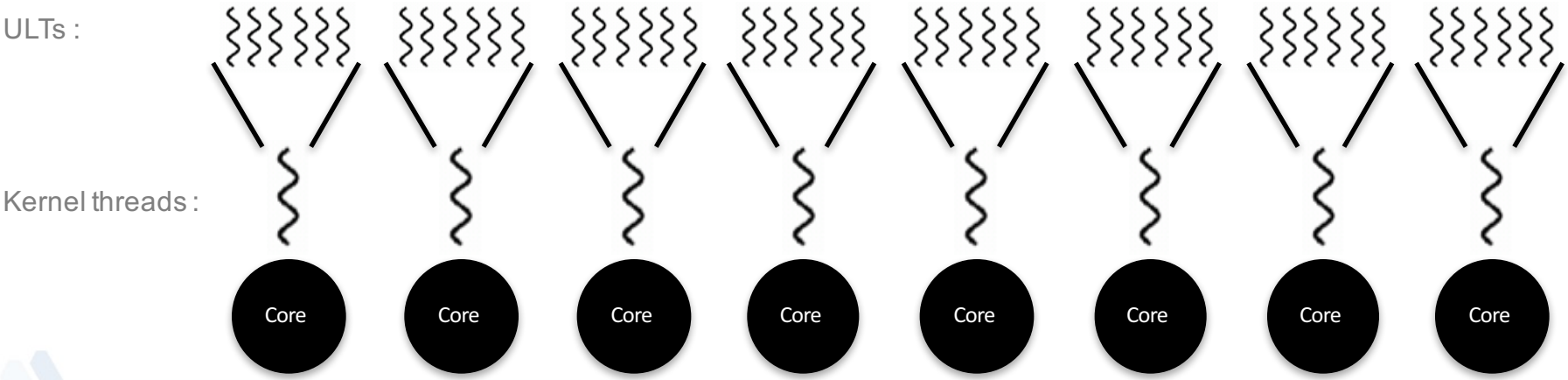
Outline

- Background
- **Argobots**
- Charm++ with Argobots
- Other Programming Models
- Summary

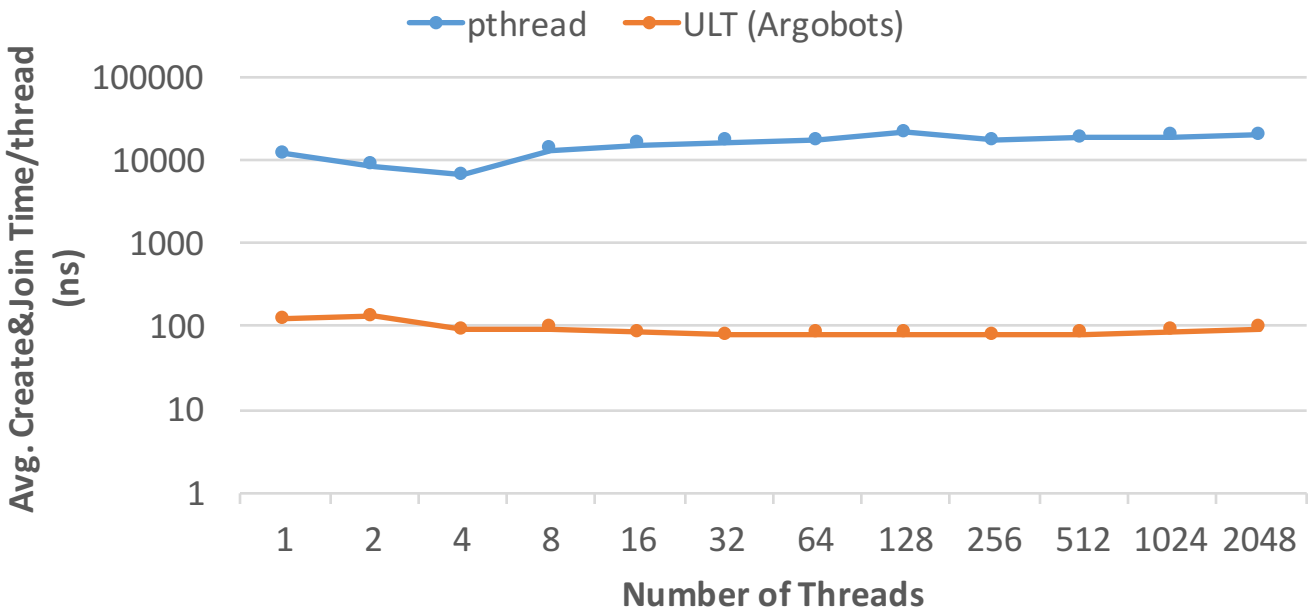
User-Level Threads (ULTs)

- 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 concurrently
- Where to use?
  - To better overlap computation and communication/IO
  - To exploit fine-grained 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

A low-level lightweight threading and tasking framework

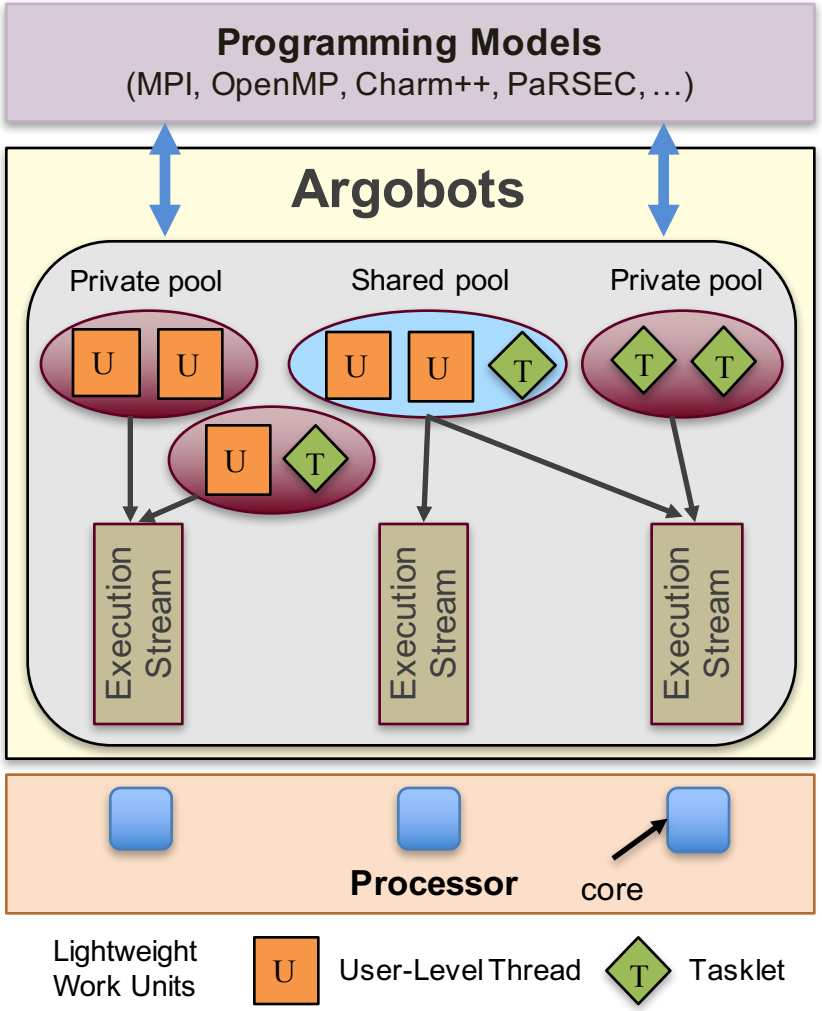
(http://collab.cels.anl.gov/display/argobots/)

Overview

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

Argobots Innovations

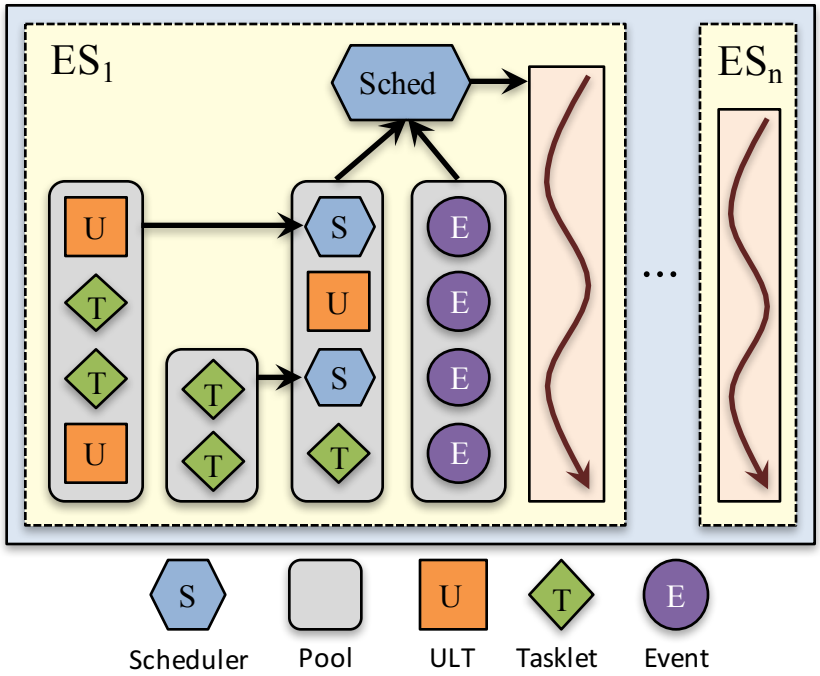
- **Enabling technology, but not a policy maker**
  - High-level languages/libraries such as OpenMP, Charm++ have more information about the user application (data locality, dependencies)
- **Explicit model**:
  - Enables dynamism, but always managed by high-level systems



* Team members: Sangmin Seo, Abdelhalim Amer, Pavan Balaji (ANL), Laxmikant Kale, Prateek Jindal (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

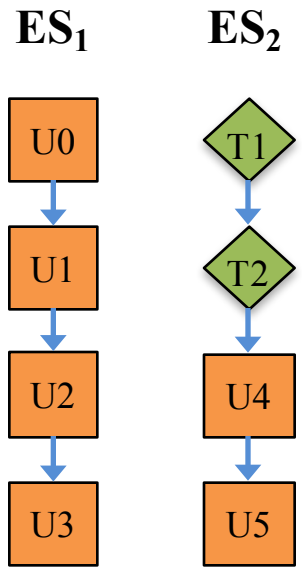


Argobots Execution Model

- **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



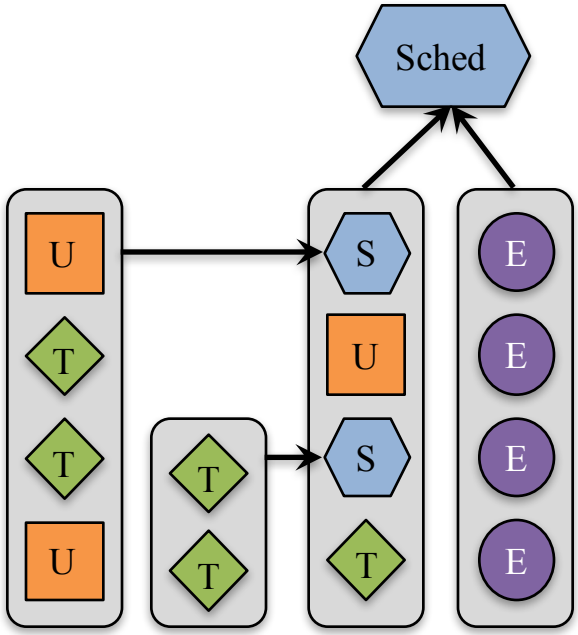
- Benefits
  - Allow locality optimization
    - Execute work units on the same ES
  - No expensive lock is needed between ULTs on the same ES
    - They do not run concurrently
    - A flag is enough

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

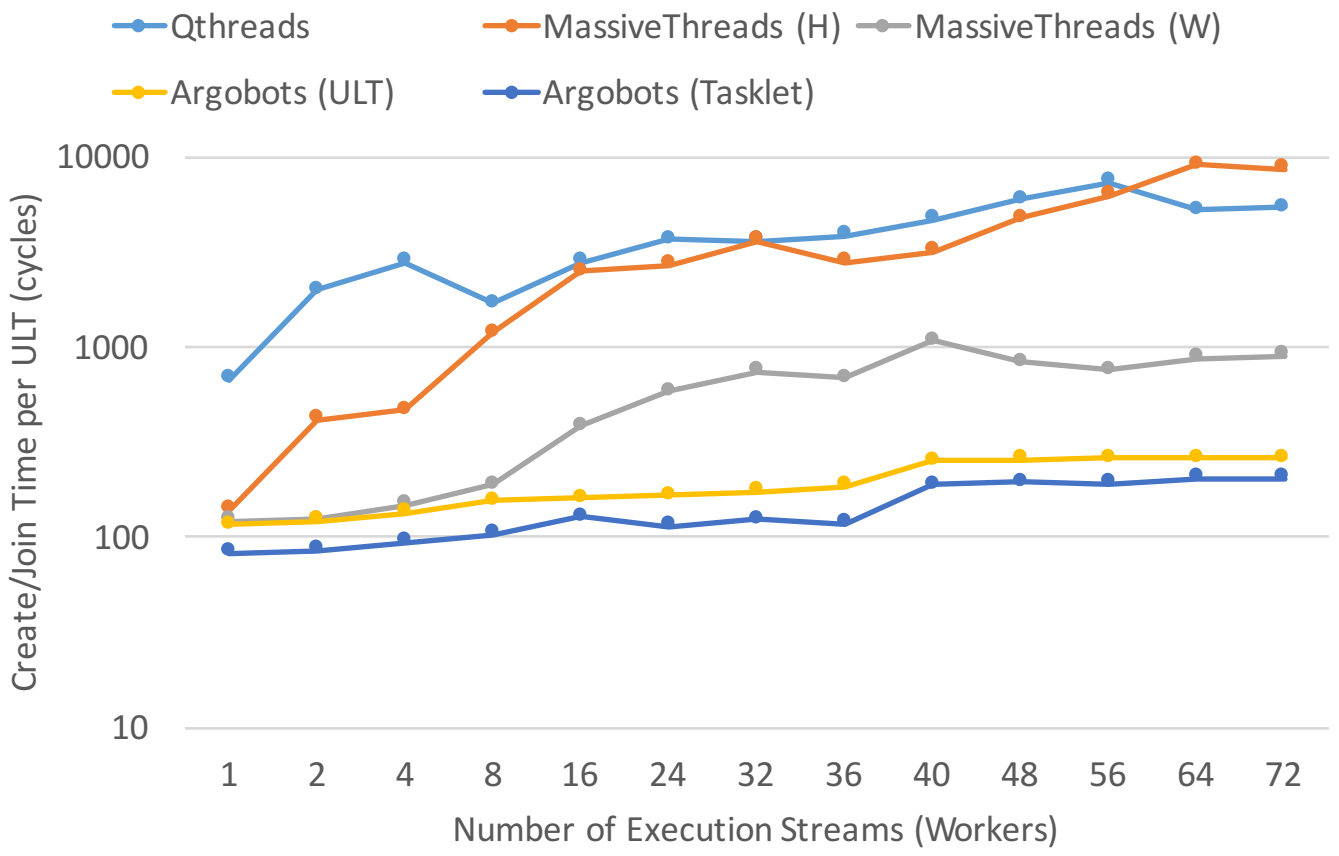
yield()

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



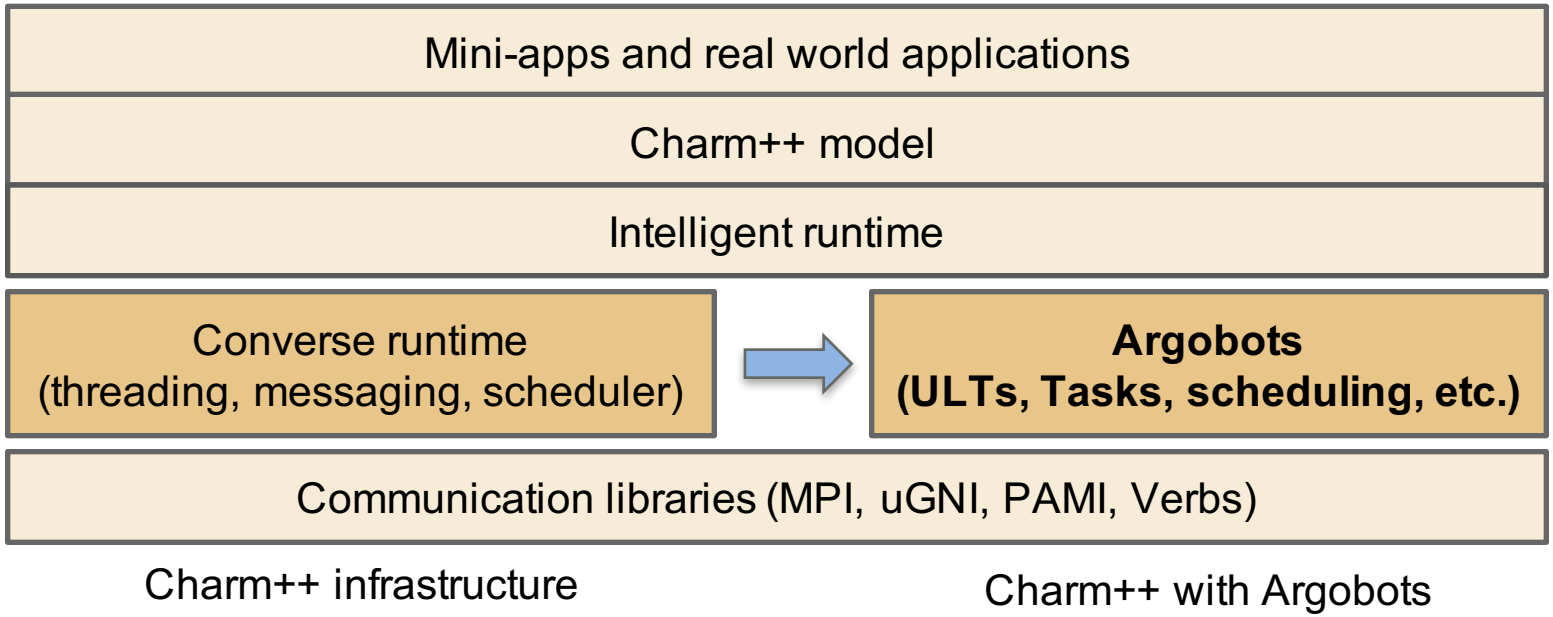
Charm++ with Argobots

Jonathan Lifflander, Prateek Jindal, Yanhua Sun
Laxmikant Kale

University of Illinois at Urbana-Champaign (UIUC)

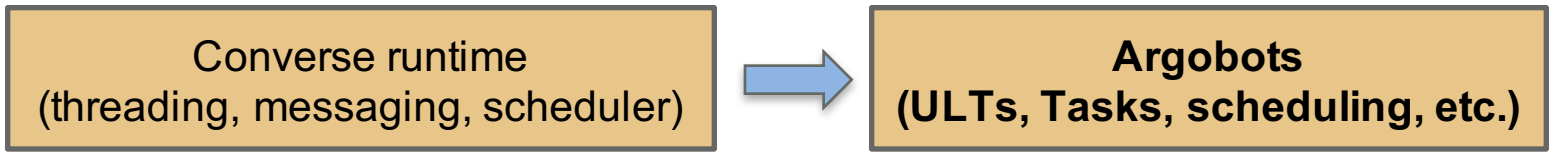
Charm++ with Argobots

- Goals
  - Test the completeness and performance of Argobots with Charm++ programming model
  - Take advantage of Argobots features (tasklets, stackable schedulers, etc.) without modifying application codes
  - For Charm++ applications, interoperate with applications written in other models (MPI, Cilk, etc.)



* Team members: Laxmikant Kale, Jonathan Lifflander, Prateek Jindal (UIUC)

Replacing the Converse Runtime with Argobots

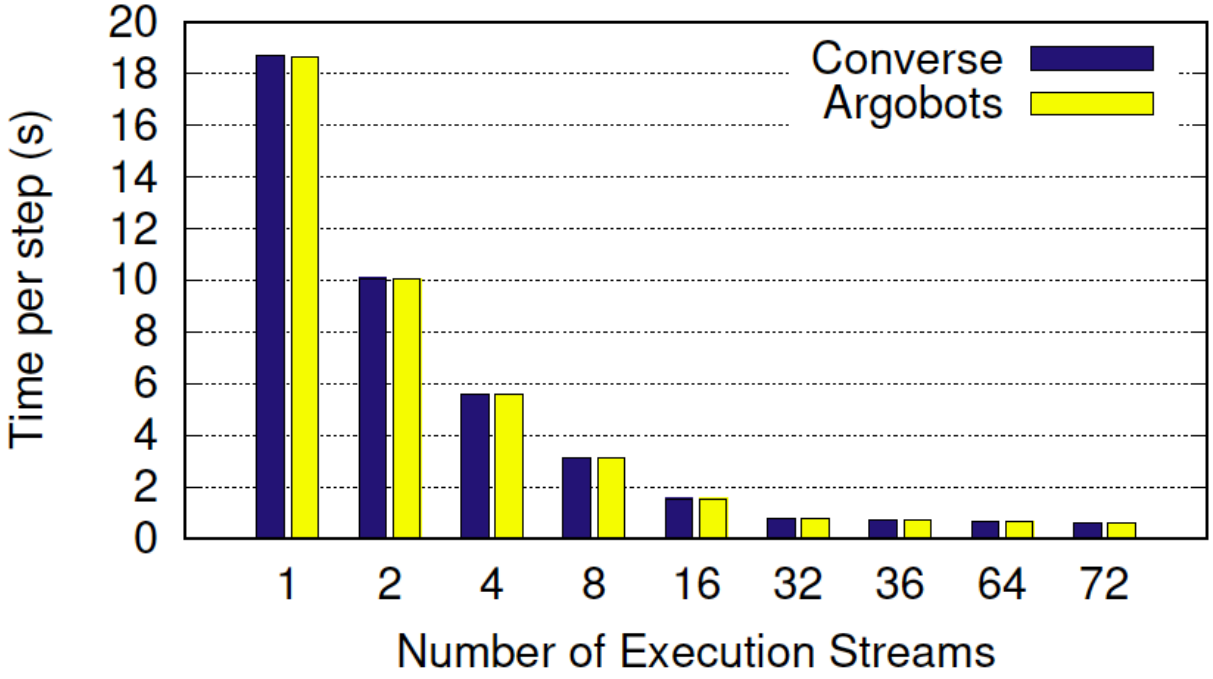


- Converse
  - The active messaging layer in Charm++
- Approaches
  - Each Charm++ Pthread inside a node (including the communication thread) is implemented as an Argobots ES
    - Create an ES for every Converse instance
  - A custom Argobots scheduler is created instead of using the Converse scheduler
  - Converse messages are enqueued into Argobots pools as tasklets
  - Converse threads (CthThread) are implemented on top of Argobots ULTs, with conditional variables to implement suspend/resume

- *Only 180 lines of code had to be changed!*

LeanMD Performance: Runtime Comparison

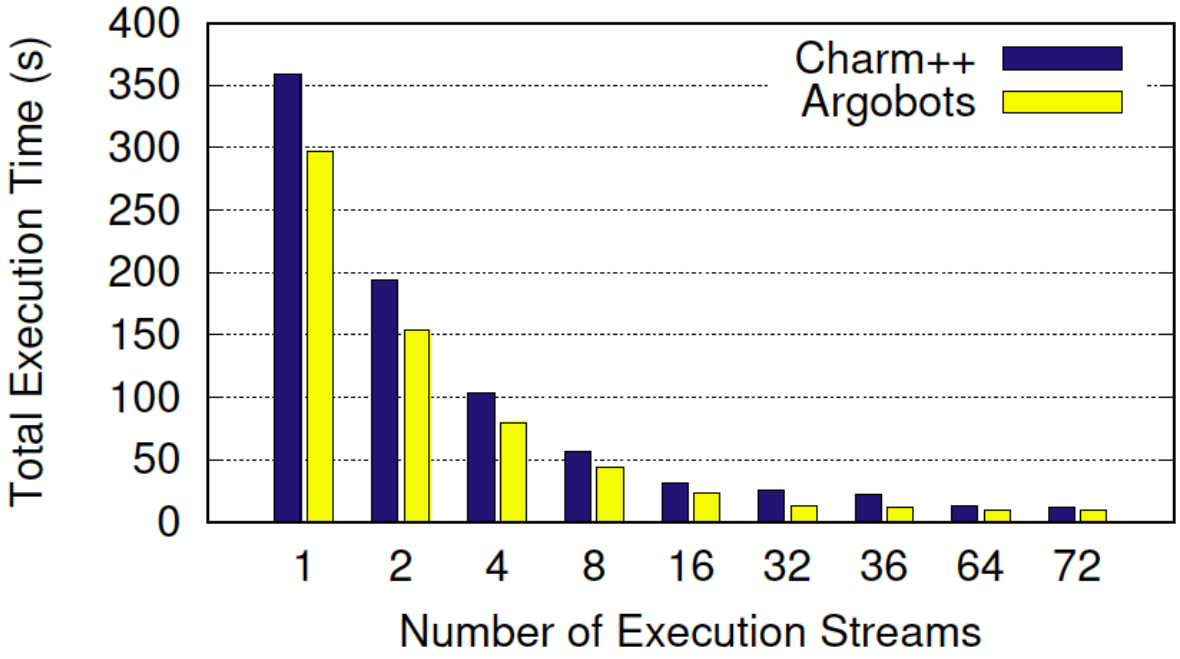
- Evaluation machine
  - 2 x Intel Xeon E5-2699 v3 (2.30GHz): 36 cores (72 threads)
- LeanMD simulation
  - A total of 20 steps on a cell array of dimensions 7x7x7
  - 1-away XYZ configuration and 1000 atoms per cell



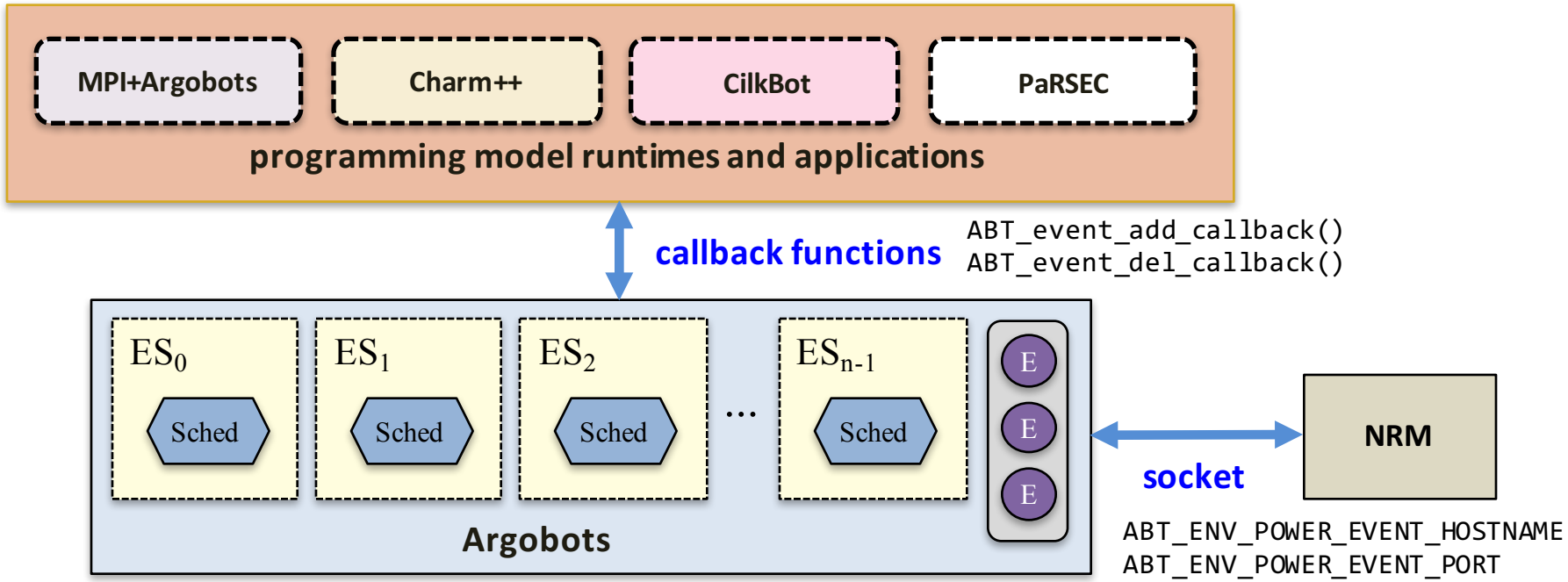
Achieved comparable performance although it is a very simple implementation

LeanMD Performance: Manual Implementation

- Manual implementation of LeanMD using the Argobots
  - Exploited both ULTs and tasklets
    - A ULT for managing a cell and a tasklet for managing the interaction between cells
  - Used futures for the waiting mechanism
  - Work stealing between pools
- Better performance of our manual implementation implies that Charm++ with Argobots could be improved



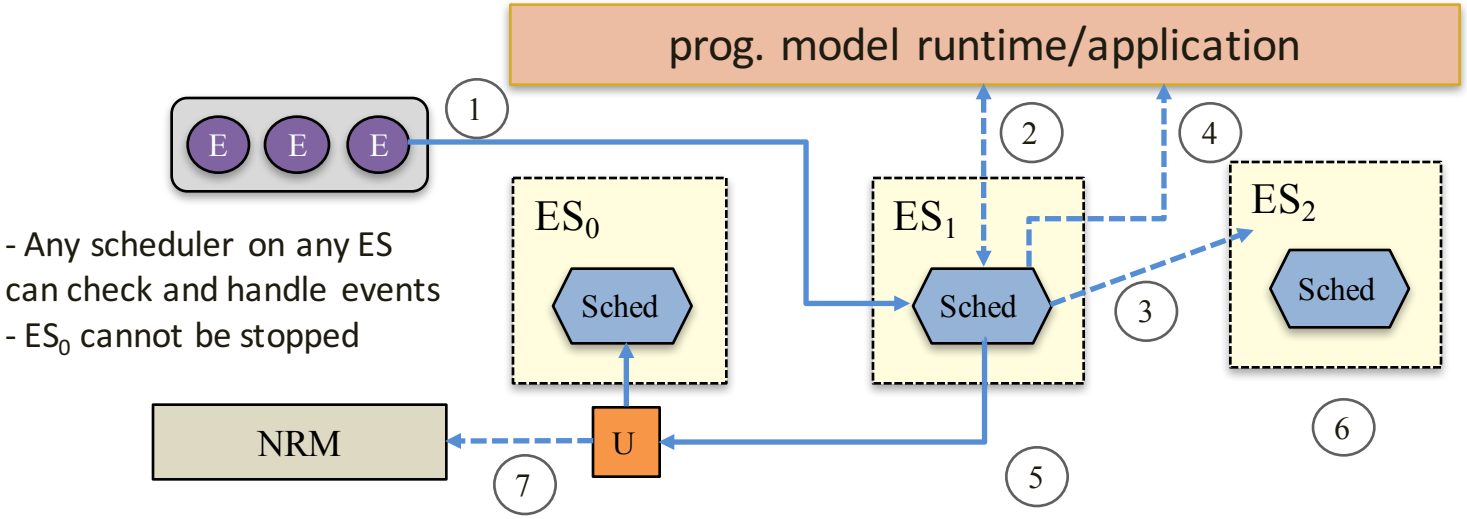
Argobots: Interfaces for Shrink/Expand Events



1. [Argobots] Connect to NRM using a socket on ABT_init()
2. [Runtimes/applications] Register callback functions for shrink/expand events
3. [Runtimes/applications] Deregister callback functions when they terminate
4. [Argobots] Disconnect from NRM on ABT_finalize()

Argobots: Shrink/Expand Event Handling

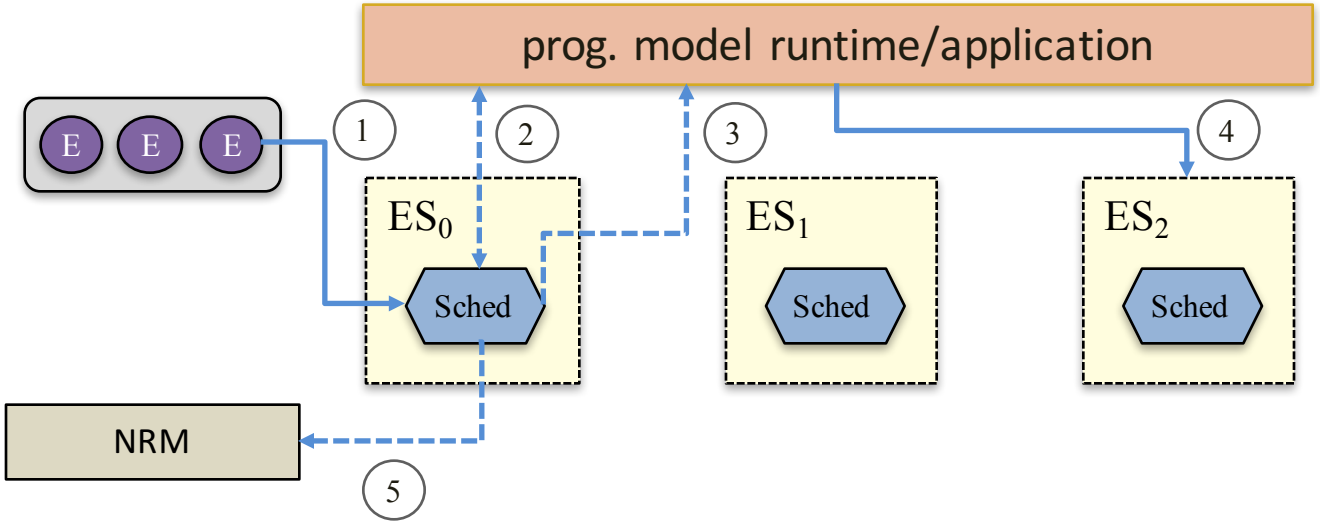
- Shrinking



1. ES_1 picks an event, which requests ES_2 to be stopped
2. Ask the runtime using callbacks whether ES_2 can be stopped
3. If OK, mark ES_2 to need to stop so when the scheduler on ES_2 checks events, it can be stopped
4. Notify the runtime that ES_2 will be stopped
5. Create a ULT on ES_0
6. When the scheduler on ES_2 stops, ES_2 is terminated
7. After ES_2 is terminated, the ULT frees ES_2 and sends a response to NRM

Argobots: Shrink/Expand Event Handling

- Expanding

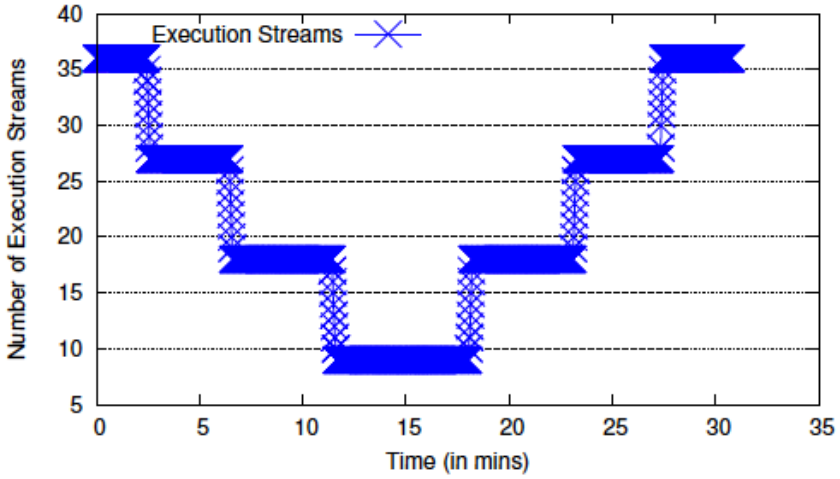


1. ES_0 picks an event, which requests to create an ES_2
2. Ask the runtime using callbacks whether it can create ES_2
3. If OK, invoke a callback function so the runtime creates ES_2
4. Create ES_2
5. Send a response to NRM

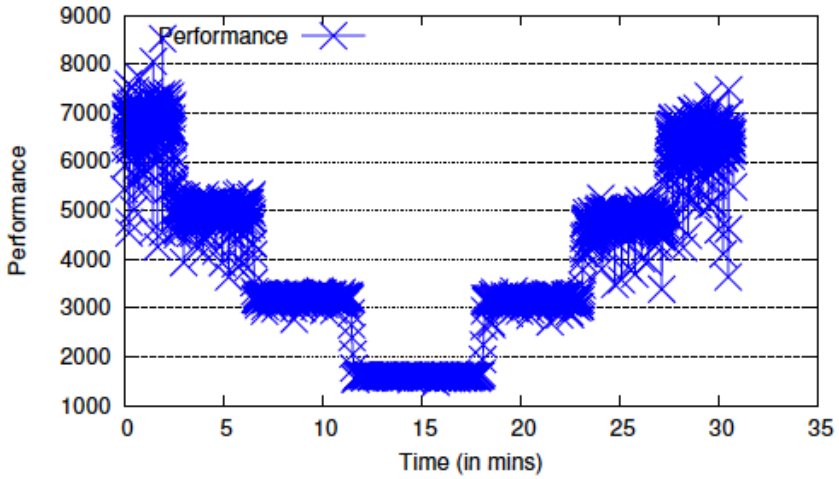
Charm++ with Argobots: Implementation

- Shrink/Expand Implementation
  - Charm++ maintains a set of pools for each scheduler, mapped to an ES
  - Ranks in Charm++ are virtualized by saving the mapping of pool to an ES
  - When an ES is removed, the associated pools are put into a global list
    - To maintain correctness in Charm++, the rank of any tasks/threads in the global list are derived from the pool (ranks are virtualized)
  - Shrink
    - Other ESs execute work units from orphaned pools with some added synchronization
  - Expand
    - A new ES is created and takes over a set of orphaned pools

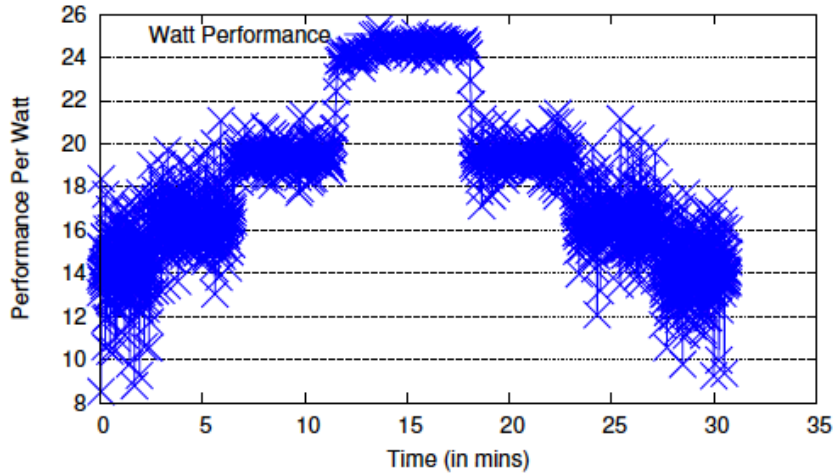
LeanMD Results of Shrinking/Expanding ESs



(a) Execution Streams

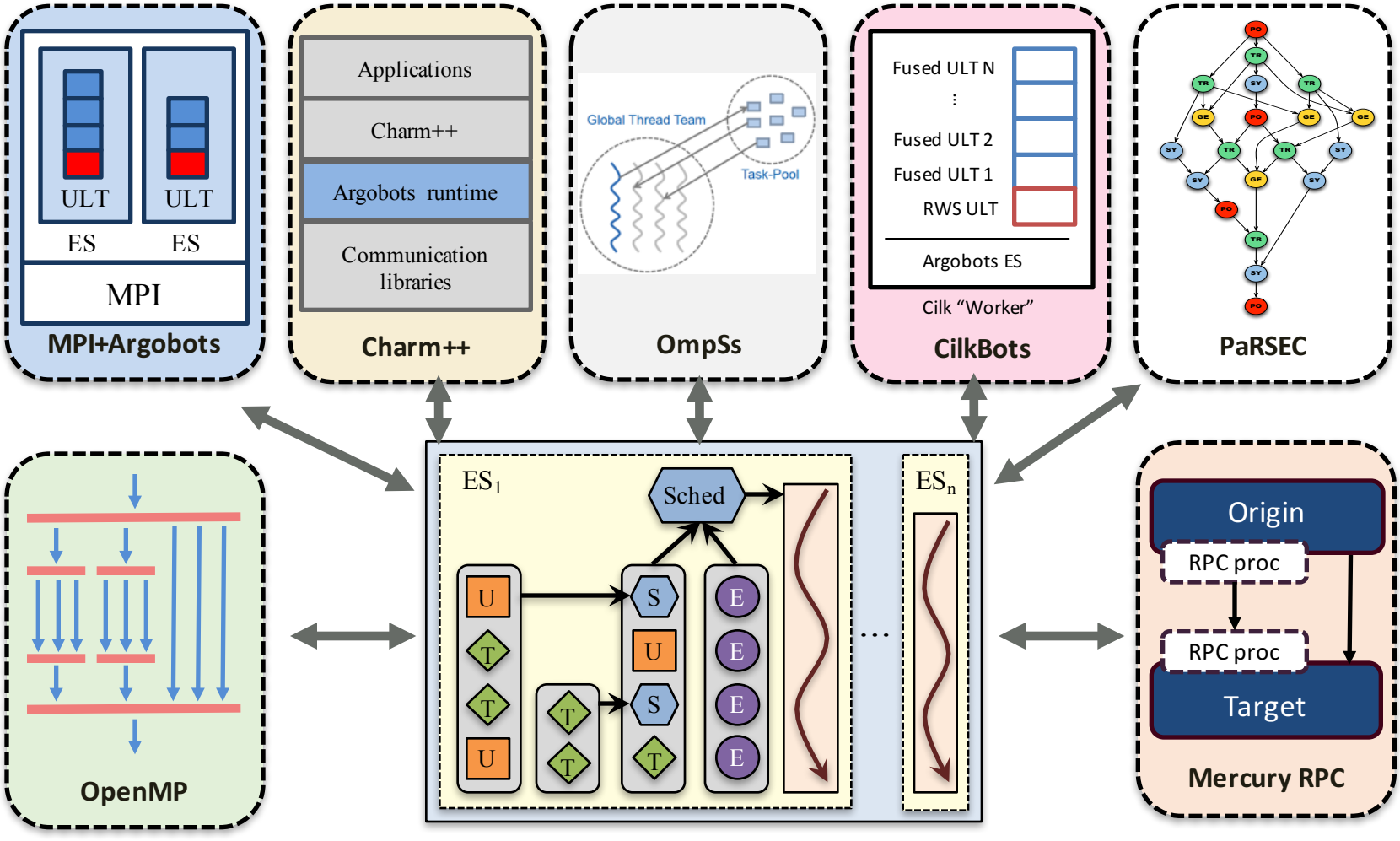


(b) Application Performance



(c) Performance per Watt

Argobots Ecosystem



Summary

- Massive on-node parallelism is inevitable
  - Need runtime systems utilizing such parallelism
- 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
- Charm++ with Argobots
  - Implemented by replacing the Converse runtime with Argobots
  - Achieved comparable performance on LeanMD
  - Incorporated the shrinking/expanding of ESs in Argobots in order to respond to the external events (e.g., power capping)

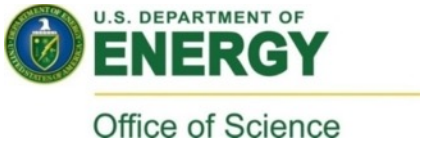
Try Argobots

- git repository
  - http://git.mcs.anl.gov/argo/argobots.git/

- Documentation
  - Wiki
    - https://collab.cels.anl.gov/display/ARGOBOTS/
  - Doxygen
    - http://www.mcs.anl.gov/~sseo/public/argobots/

Funding Acknowledgments

Funding Grant Providers



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- Ken Raffenetti (developer)
- Sangmin Seo (assistant computer scientist)
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- David J. Goodell (developer)
- Huiwei Lu (postdoc)
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- Marc Snir (division director)
- Rajeev Thakur (deputy director)

Q&A

- Thank you for your attention!

Questions?