Lightweight Threaded Runtime Systems for OpenMP

Shintaro Iwasaki

Argonne National Laboratory, The University of Tokyo

Email: siwasaki@anl.gov, iwasaki@eidos.ic.i.u-tokyo.ac.jp

Outline of This Talk

- BOLT: a lightweight OpenMP library based on LLVM OpenMP.
  - It uses a lightweight user-level thread for OpenMP task and thread.
- BOLT won the Best Paper Award at PACT '19[*]

- Features of BOLT:

We will focus on this.

1. Extremely lightweight OpenMP threads that can efficiently handle nested parallelism.
2. ~~Tackle an interoperability issue of MPI + OpenMP task.~~

- This presentation will cover how to handle nested parallelism of BOLT.
  - Please visit us! https://www.bolt-omp.org/ or google "BOLT OpenMP"

[*] S. Iwasaki et al., "BOLT: Optimizing OpenMP Parallel Regions with User-Level Threads", PACT '19, 2019

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OpenMP: the Most Popular Multithreading Model

- Multithreading is essential for exploiting modern CPUs.

OpenMP® Enabling HPC since 1997

- OpenMP is a popular parallel programming model.
  - In the HPC field, OpenMP is most popular for multithreading.
    - 57% of DOE exascale applications use OpenMP [*].

- Not only user programs but also runtimes and libraries are parallelized by OpenMP.

DNN library

Kokkos, RAJA, OpenBLAS, Intel MKL, SLATE, Intel MKL-DNN, FFTW3, …

Runtimes that have an OpenMP backend

BLAS/LAPACK libraries

FFTW library

[*] D. E. Bernholdt et al. "A Survey of MPI Usage in the US Exascale Computing Project", Concurency Computat Pract Expr, 2018

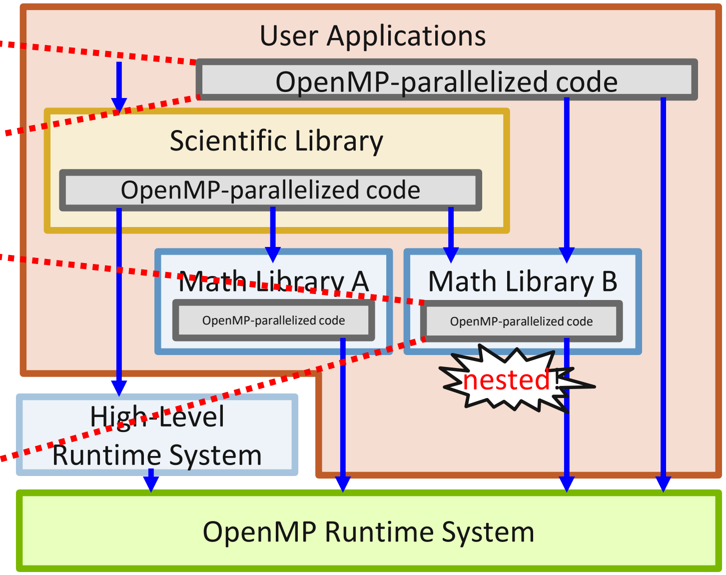
Unintentional Nested OpenMP Parallel Regions

```
#pragma omp parallel for
for (i = 0; i < n; i++)
  dgemv(matrix[n], ...);
```

```
// BLAS library
void dgemv(...) {
  #pragma omp parallel for
  for (i = 0; i < n; i++)
    dgemv_seq(data[n], i);
}
```

nested!

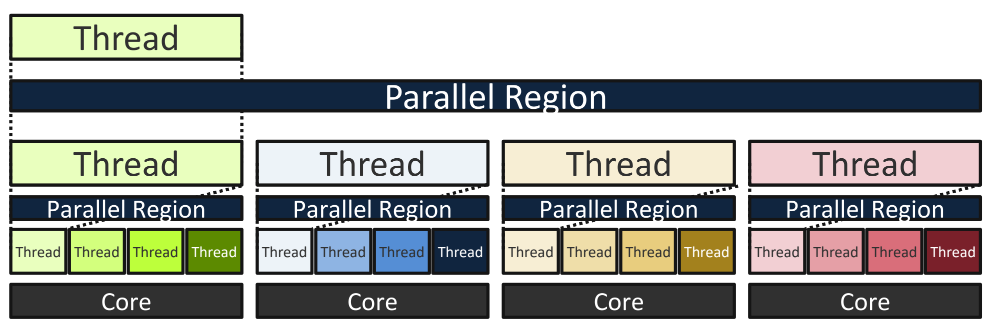
Code Example



- OpenMP parallelizes multiple software stacks.
- Nested parallel regions create OpenMP threads exponentially.

```
#pragma omp parallel for
for (i = 0; i < n; i++)
  dgemm(matrix[n], ...);
```

```
void dgemm(...):
  #pragma omp parallel for
  for (i = 0; i < n; i++);
```



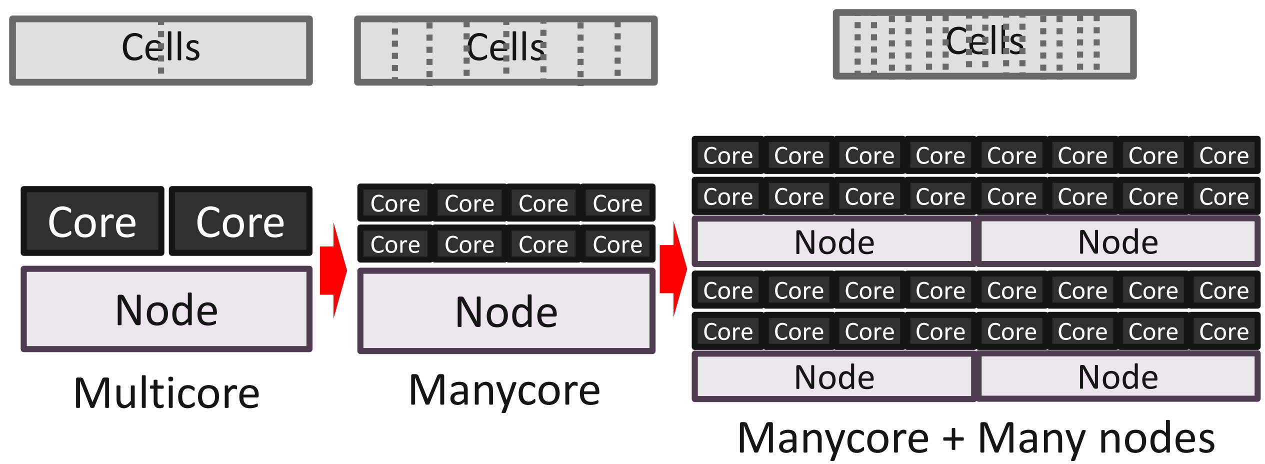
Can We Just Disable Nested Parallelism?

- How to utilize nested parallel regions?
  - Enable nested parallelism: creation of exponential the number of threads
  - Disable nested parallelism: adversely decrease parallelism
- Example: strong scaling on massively parallel machines

Is the outer parallelism enough to feed work to all the cores???

```
#pragma omp parallel for
for (i = 0; i < n; i++)
  comp(cells[i], ...);
```

```
void comp(...):
  [...];
  #pragma omp parallel for
  for (i = 0; i < n; i++);
```



Two Directions to Address Nested Parallelism

- Nested parallel regions have been known as a problem since OpenMP 1.0 (1997).
  - By default, OpenMP disables nested parallelism[*].
- Two directions to address this issue:

  1. Use several work arounds implied in the OpenMP specification.

  => Not practical if users do not know parallelism at other software stacks.

  2. Instead of OS-level threads, use lightweight threads as OpenMP threads

  User-level threads (ULTs, explained later)

  => It does not perform well if parallel regions are not nested (i.e., flat).

  - It does not perform well even when parallel regions are nested.

=> Need a solution to efficiently utilize nested parallelism.

[*] Since OpenMP 5.0, the default becomes "implementation defined", while most OpenMP systems continue to disable nested parallelism by default.

BOLT: Lightweight OpenMP over ULT for Both Flat & Nested Parallel Regions

- We proposed BOLT, a ULT-based OpenMP runtime system, which performs best for both flat and nested parallel regions.

- Three key contributions:
  1. An in-depth performance analysis in the LLVM OpenMP runtime, finding several performance barriers.
  2. An implementation of thread-to-CPU binding interface that supports user-level threads.
  3. A novel thread coordination algorithm to transparently support both flat and nested parallel regions.

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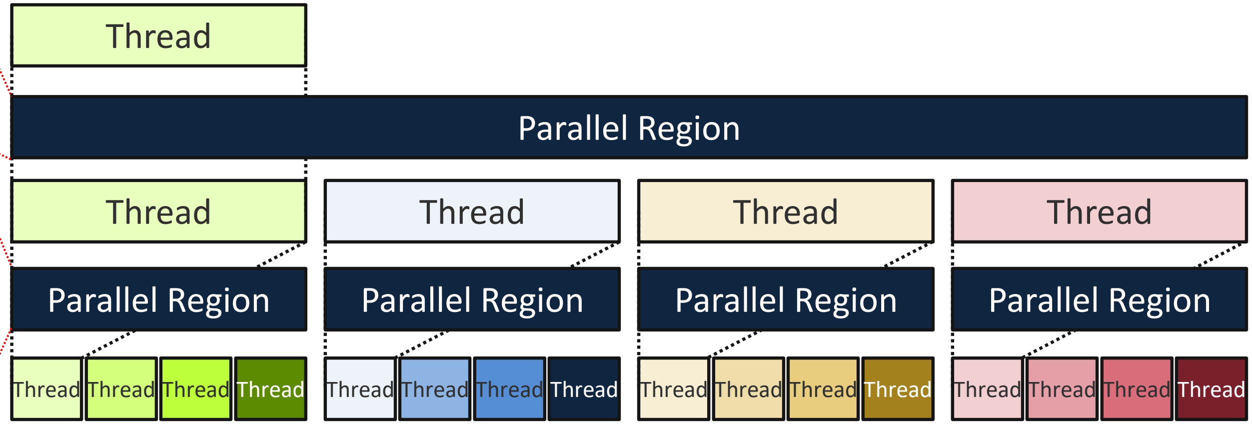
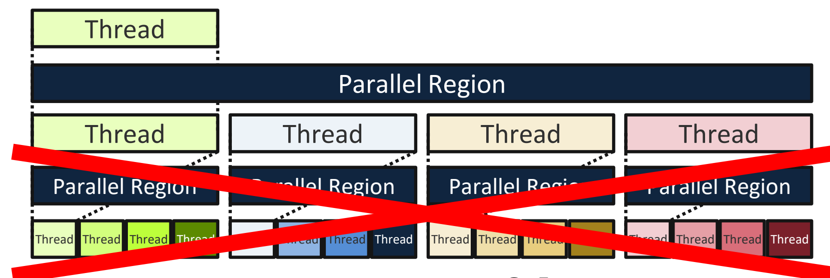
Direction 1: Work around with OS-Level Threads (1/2)

```
#pragma omp parallel for
for (i = 0; i < n; i++)
  dgemv(matrix[n], ...);
```

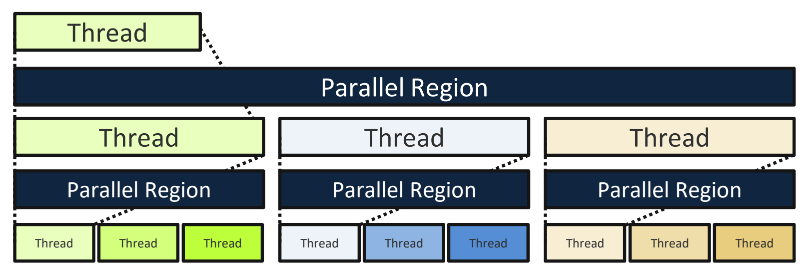
```
// BLAS library
void dgemv(...) {
  #pragma omp parallel for
  for (i = 0; i < n; i++)
    dgemv_seq(data[n], i);
}
```



- Several workarounds
  1. Disable nested parallel regions (`OMP_NESTED=false, OMP_ACTIVE_LEVELS=...`)
     - Parallelism is lost.
  2. Finely tune numbers of threads (`OMP_NUM_THREADS=nth1,nth2,nth3,...`)
     - Parallelism is lost. Difficult to tune parameters.



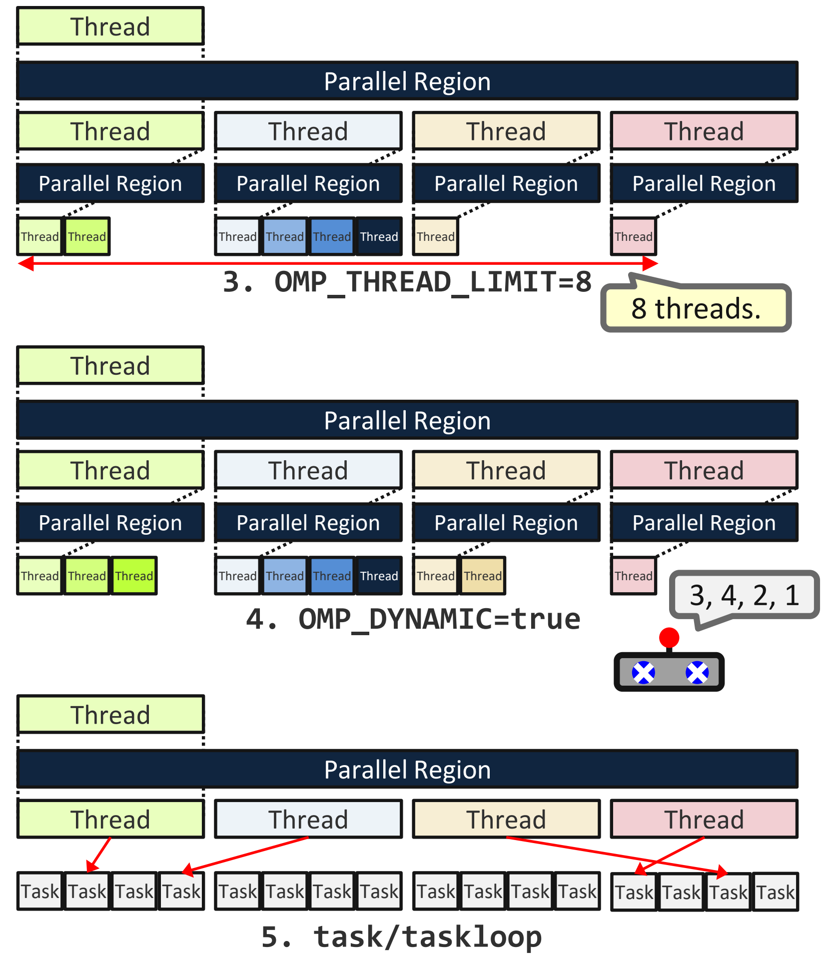
1. `OMP_NESTED=false`



2. `OMP_NUM_THREADS=3,3`

Direction 1: Work around with OS-Level Threads (2/2)

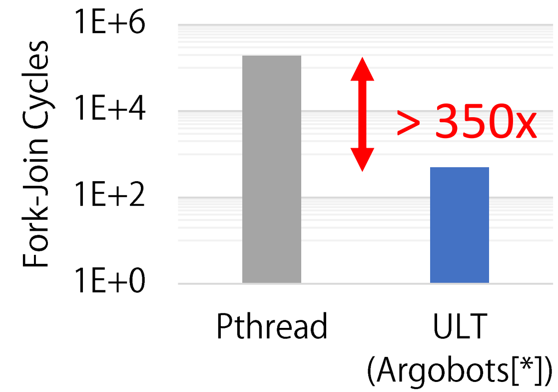
- Workarounds (cont.)
  3. Limit the total number of threads (`OMP_THREAD_LIMIT=nths`)
     - Can adversely serialize parallel regions; doesn't work well in practice.
  4. Dynamically adjust # of threads (OMP_DYNAMIC=true)
     - Can adversely serialize parallel regions; doesn't work well in practice.
  5. Use OpenMP task (`#pragma omp task/taskloop`)
     - Most codes use parallel regions. Semantically, threads != tasks.



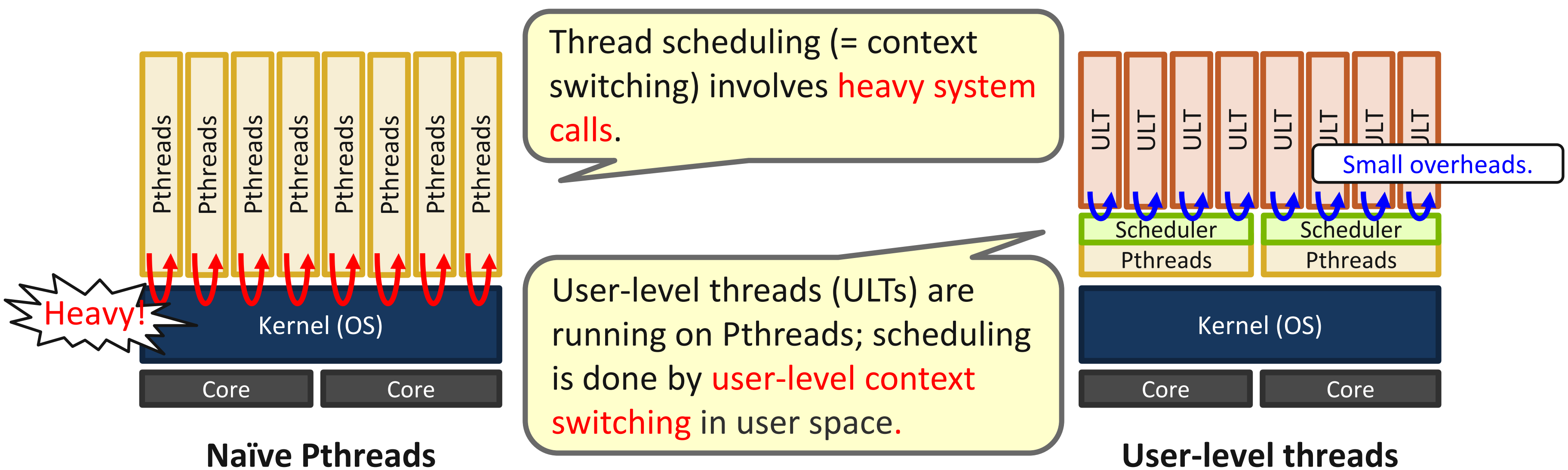
- How about using lightweight threads for OpenMP threads?

Direction 2: Use Lightweight Threads => User-Level Threads (ULTs)

- User-level threads: threads implemented in user-space.
  - Manages threads without heavyweight kernel operations.

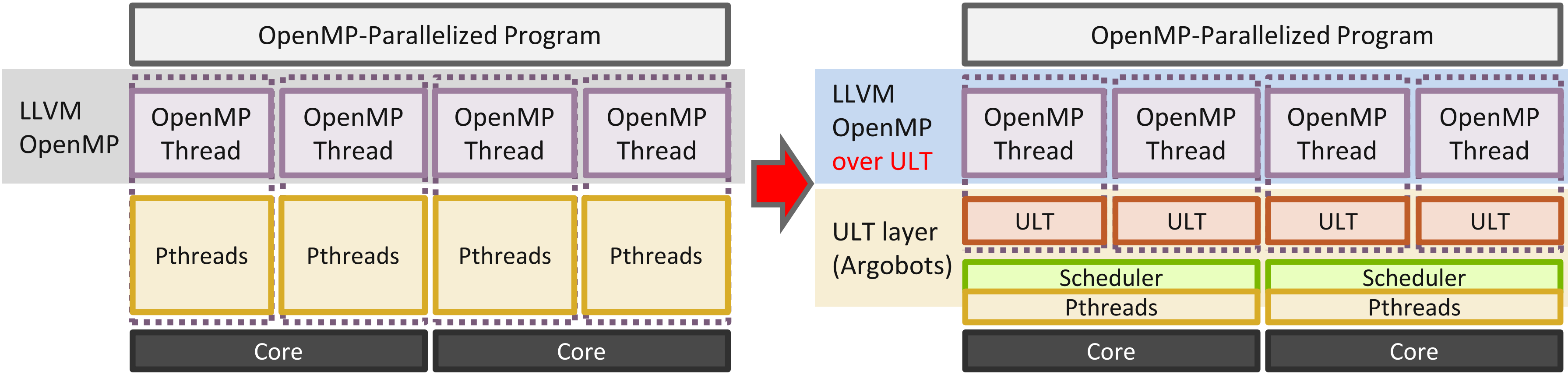


Fork-Join Performance on KNL



[*] S. Seo et al. "Argobots: A Lightweight Low-Level Threading and Tasking Framework", TPDS '18, 2018

Using ULTs is Easy



LLVM OpenMP 7.0 **LLVM OpenMP 7.0 over ULT (= BOLT baseline)**

- Replacing a Pthreads layer with a user-level threading library is a piece of cake.
  - Argobots[*] we used in this paper has the Pthreads-like API (mutex, TLS, ...), making this process easier.

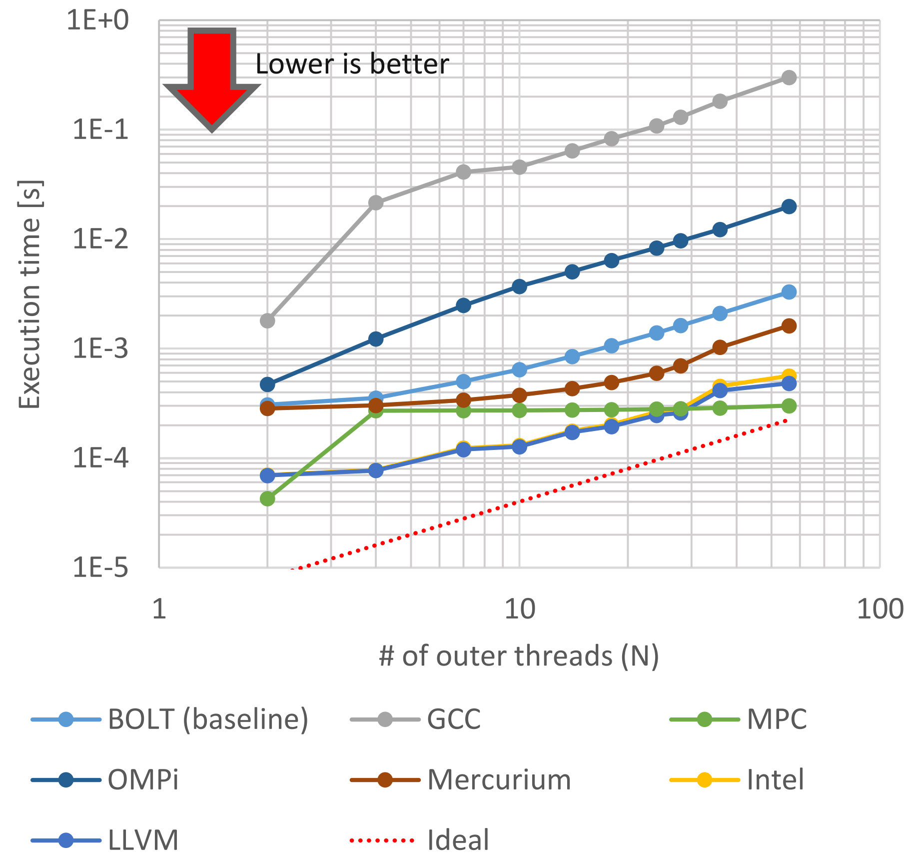
    Note: other ULT libraries (e.g., Qthreads, Nanos++, MassiveThreads ...) also have similar threading APIs.
  - The ULT-based OpenMP implementation is OpenMP 4.5-compliant (as far as we examined)
- Does the “baseline BOLT” perform well?

[*] S. Seo et al. "Argobots: A Lightweight Low-Level Threading and Tasking Framework", TPDS '18, 2018

Simple Replacement Performs Poorly

```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(N)
for (int i = 0; i < N; i++)
  #pragma omp parallel for num_threads(28)
  for (int j = 0; j < 28; j++)
    comp_20000_cycles(i, j);
```

Nested Parallel Region (balanced)



- Faster than GNU OpenMP.
  - GCC
- So-so among ULT-based OpenMPs
  - MPC, OMPi, Mercurium
- Slower than Intel/LLVM OpenMPs.
  - Intel, LLVM

Popular Pthreads-based OpenMP

State-of-the-art ULT-based OpenMP

GCC: GNU OpenMP with GCC 8.1
Intel: Intel OpenMP with ICC 17.2.174
LLVM: LLVM OpenMP with LLVM/Clang 7.0
MPC: MPC 3.3.0
OMPi: OMPi 1.2.3 and psthreads 1.0.4
Mercurium: OmpSs (OpenMP 3.1 compat) 2.1.0 + Nanos++ 0.14.1

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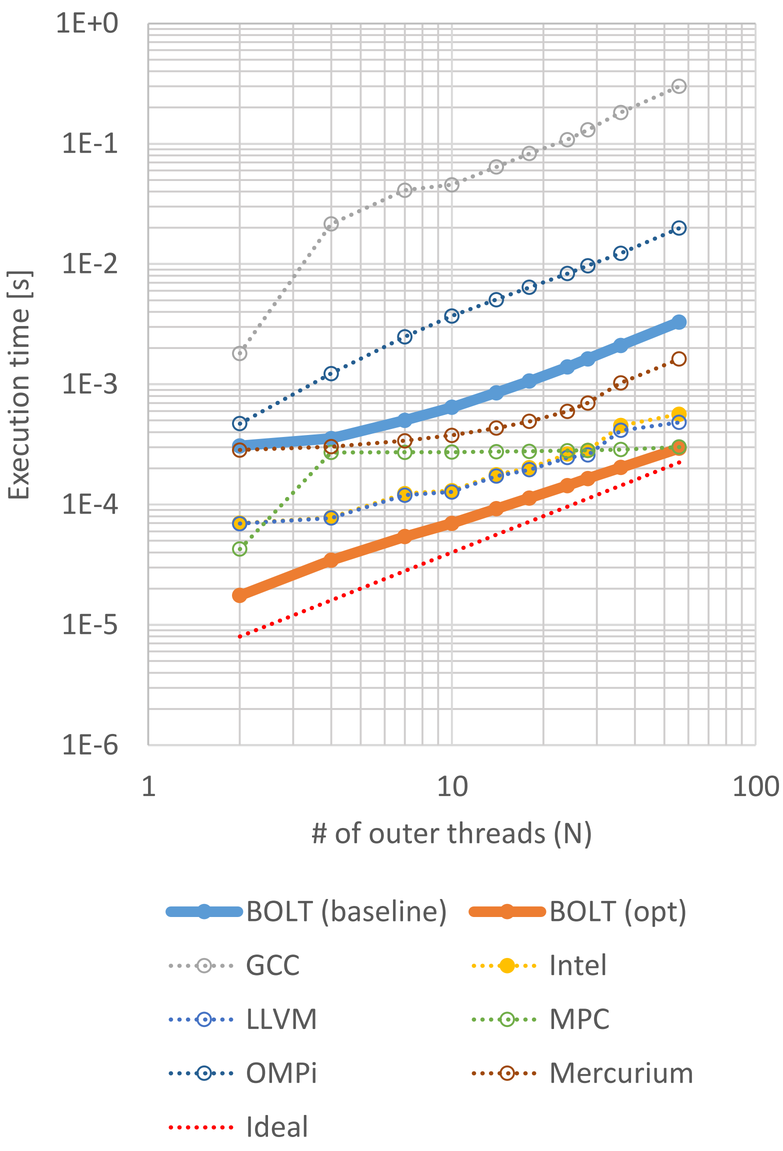
1. Introduction
2. **User-level threads for OpenMP threads**
   - Nested parallel regions and issues
   - **Efficient adoption of ULTs**
   - Evaluation
3. User-level threads for OpenMP tasks
   - OpenMP task and MPI operations
   - Tasking over ULT-aware MPI
4. Conclusions and future work

Three Optimization Directions for Further Performance

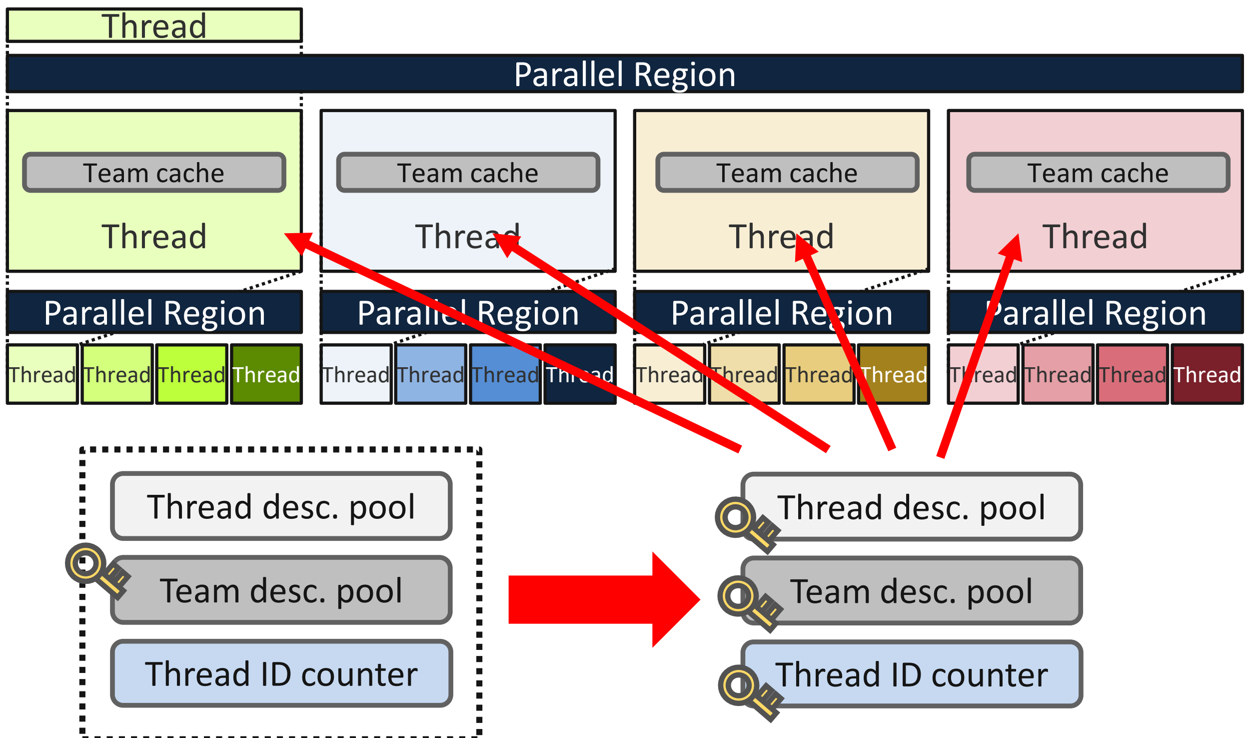
```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(N)
for (int i = 0; i < N; i++)
  #pragma omp parallel for num_threads(28)
  for (int j = 0; j < 28; j++)
    comp_20000_cycles(i, j);
```

Nested Parallel Region (balanced)

- The naïve replacement (BOLT (baseline)) does not perform well.
- Need advanced optimizations
  1. Solving scalability bottlenecks
  2. ULT-friendly affinity
  3. Efficient thread coordination



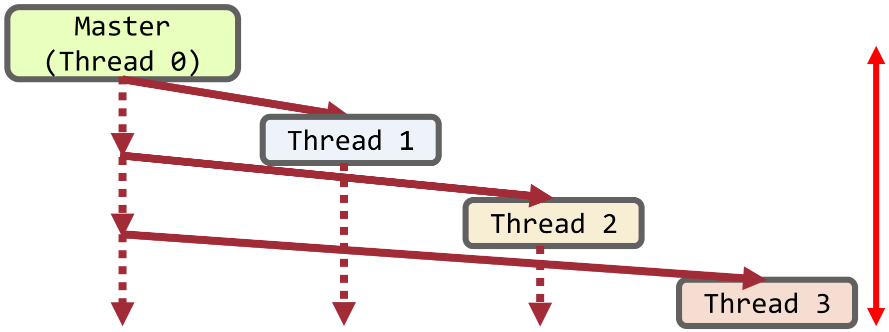
1. Solve Scalability Bottlenecks (1/2)



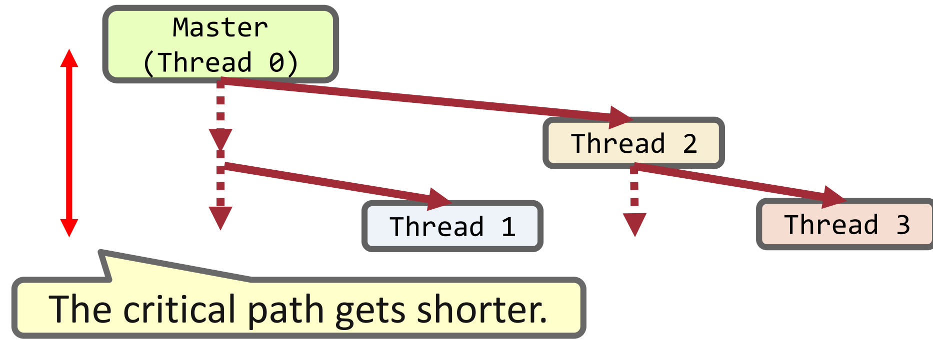
- Resource management optimizations
  1. Divides a large critical section protecting all threading resources.
     - This cost is negligible with Pthreads.
  2. Enable multi-level caching of parallel regions
     - Called “nested hot teams” in LLVM OpenMP.

1. Solve Scalability Bottlenecks (2/2)

- Thread creation optimizations
  3. Binary creation of OpenMP threads.



Serial Thread Creation (default LLVM OpenMP)

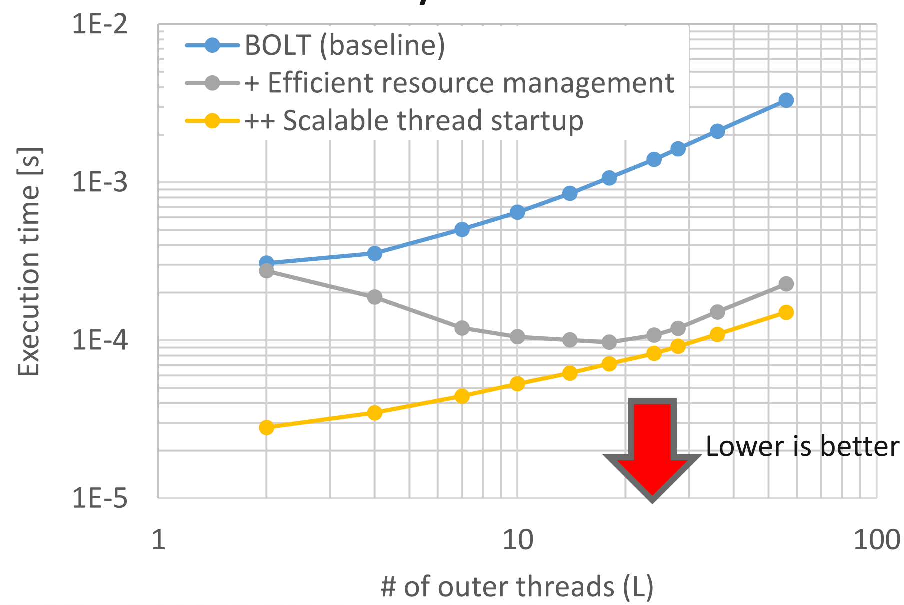


Binary Thread Creation

```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(L)
for (int i = 0; i < L; i++)
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++)
    no_comp();
```

Nested Parallel Regions (no computation)

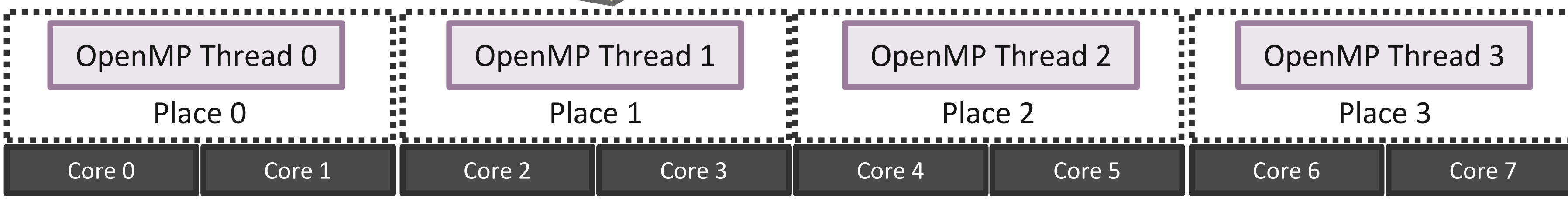
No computation to measure the pure overheads.



2. Affinity: How to Implement Affinity for ULTs

```
// OMP_PLACES={0,1},{2,3},{4,5},{6,7}
// OMP_PROC_BIND=spread
#pragma omp parallel for num_threads(4)
for (i = 0; i < 4; i++)
  comp(i);
```

With proc_bind, threads are bound to places.

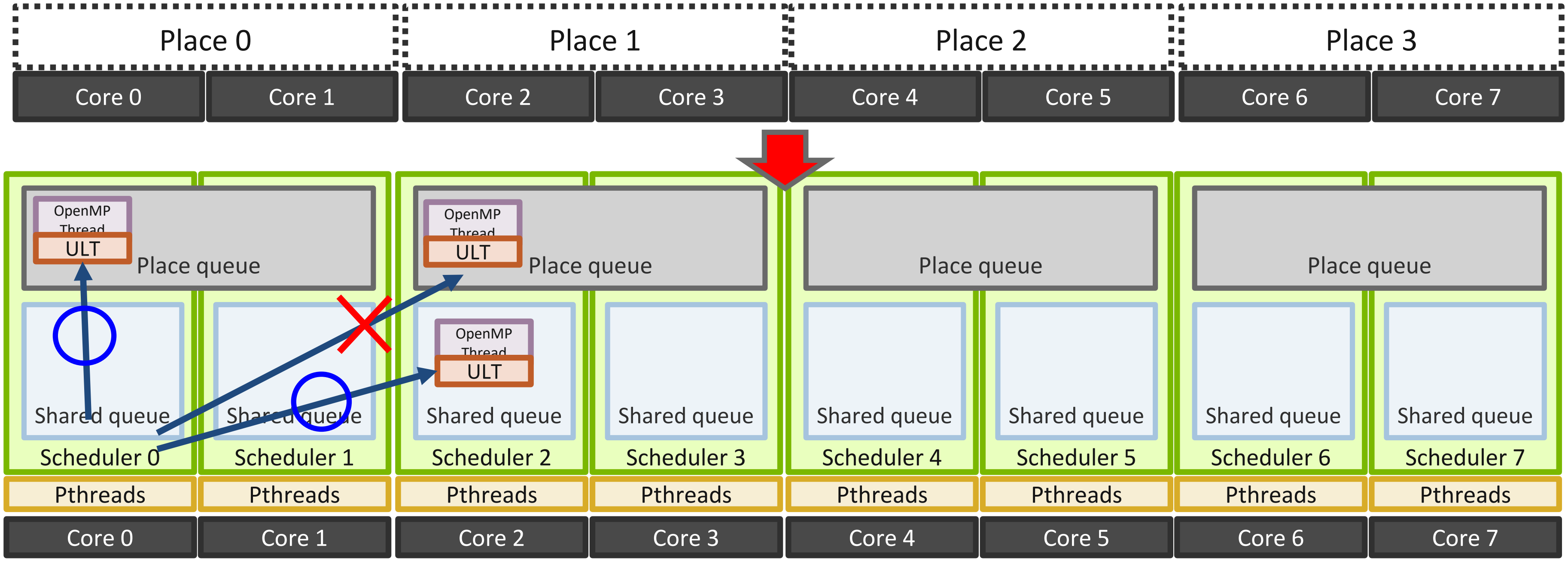


- OpenMP 4.0 introduced *place* and *prod_bind* for affinity.
  - OS-level thread-based libraries (e.g., GNU OpenMP) use CPU masks.
- BOLT (baseline) ignored affinity (still standard compliant).
- However, affinity should be useful to
  1. improve locality and 2. reduce queue contentions.
  - Note: ULT runtimes use shared queues + random work stealing.
- *How to implement place over ULTs*?

Implementation: Place Queue

- *Place queues* can implement OpenMP affinity in BOLT.

```
// OMP_PLACES={0,1},{2,3},{4,5},{6,7}
// OMP_PROC_BIND=spread
#pragma omp parallel for num_threads(4)
for (i = 0; i < 4; i++)
  comp(i);
```



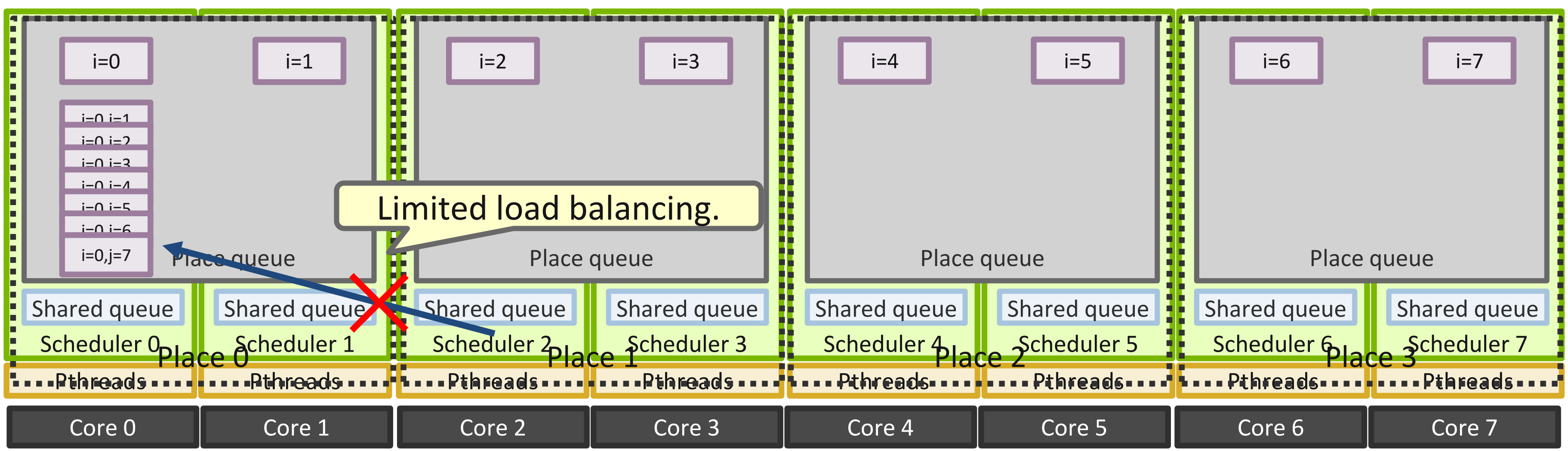
- Problem: OpenMP affinity setting is too deterministic.

OpenMP Affinity is Too Deterministic

- Affinity (or bind-var) is once set, all the OpenMP threads created in the descendant parallel regions are bound to places.

```
// OMP_PLACES={0,1},{2,3},{4,5},{6,7}
// OMP_PROC_BIND=spread
#pragma omp parallel for num_threads(8)
for (int i = 0; i < 8; i++)
  #pragma omp parallel for num_threads(8)
  for (int j = 0; j < 8; j++)
    comp(i, j);
```

The OpenMP specification writes so.



- Promising direction: scheduling innermost threads with unbound random work stealing.

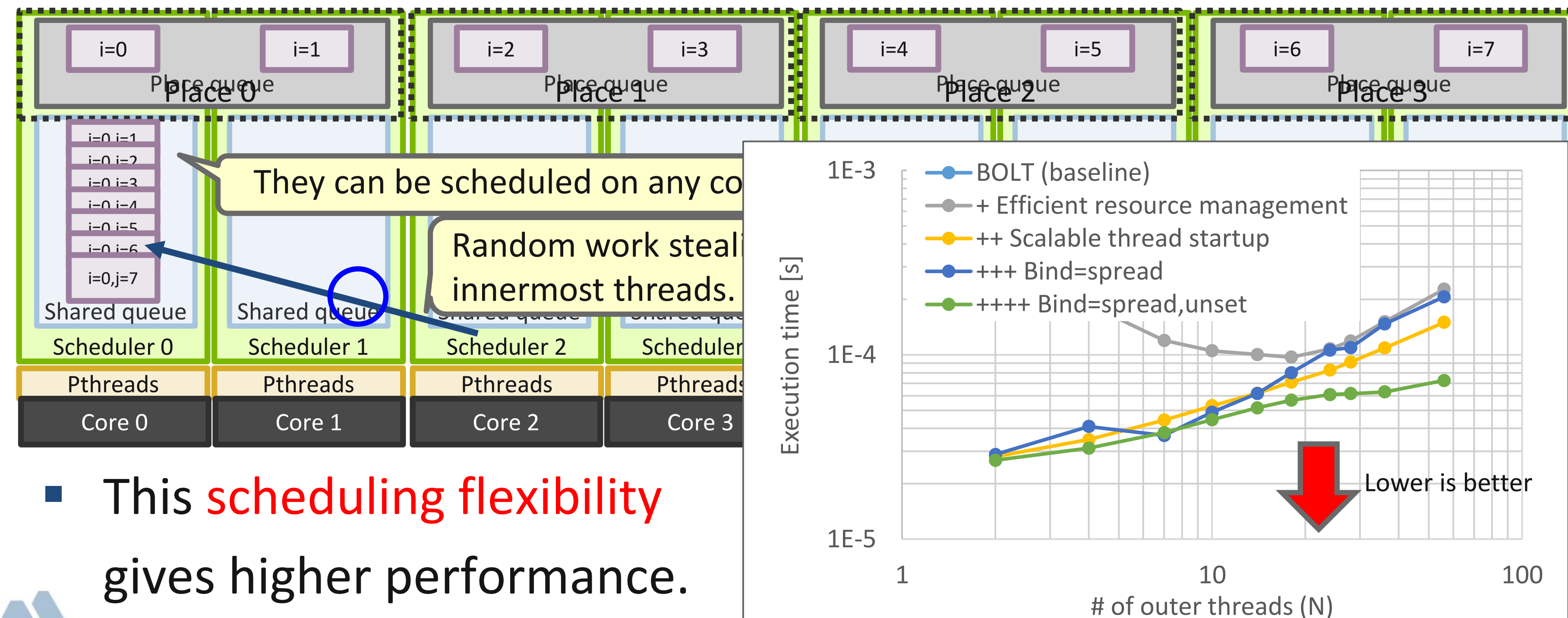
Proposed New PROC_BIND: “unset”

`OMP_WAIT_POLICY=unset`: reset the affinity setting of the specified parallel region.

(Detailed: The `unset` thread affinity policy resets the *bind-var* ICV and the *place-partition-var* ICV to their implementation defined values and instructs the execution environment to follow these values.)

```c
// OMP_PLACES={0,1},{2,3},{4,5},{6,7}
// OMP_PROC_BIND=spread
#pragma omp parallel for num_threads(8)
for (int i = 0; i < 8; i++)
  #pragma omp parallel for num_threads(8)
  for (int j = 0; j < 8; j++)
    comp(i, j);
```

```c
// OMP_PLACES={0,1},{2,3},{4,5},{6,7}
// OMP_PROC_BIND=spread,unset
#pragma omp parallel for num_threads(8)
for (int i = 0; i < 8; i++)
  #pragma omp parallel for num_threads(8)
  for (int j = 0; j < 8; j++)
    comp(i, j);
```



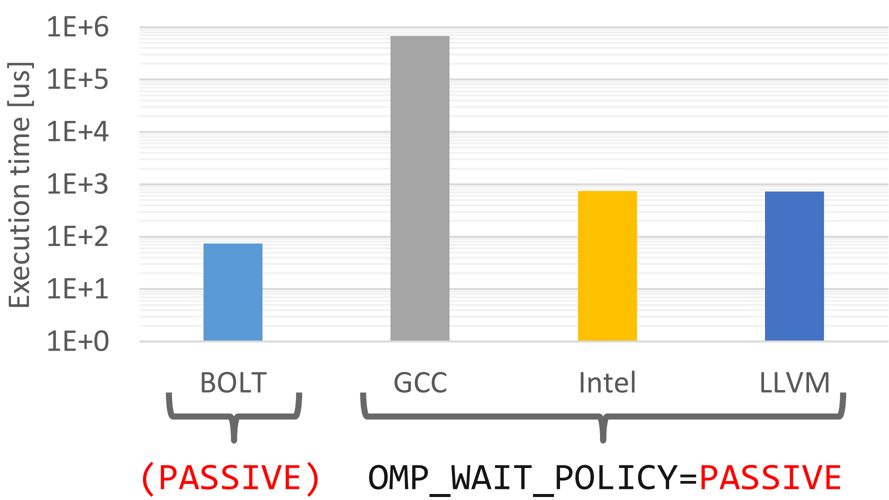
- This scheduling flexibility gives higher performance.

3. Flat Parallelism: Poor Performance

- BOLT should perform as good as the original LLVM OpenMP.

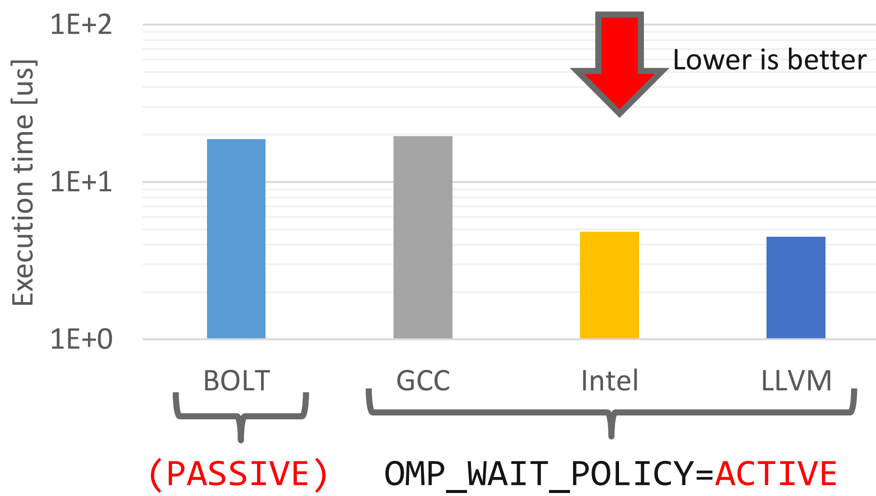
Nested Parallel Regions (no computation)

```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++) no_comp(i, j);
```



Flat Parallel Region (no computation)

```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  no_comp(i);
```



- Optimal `OMP_WAIT_POLICY` for GCC/Intel/LLVM improves performance of flat parallelism.

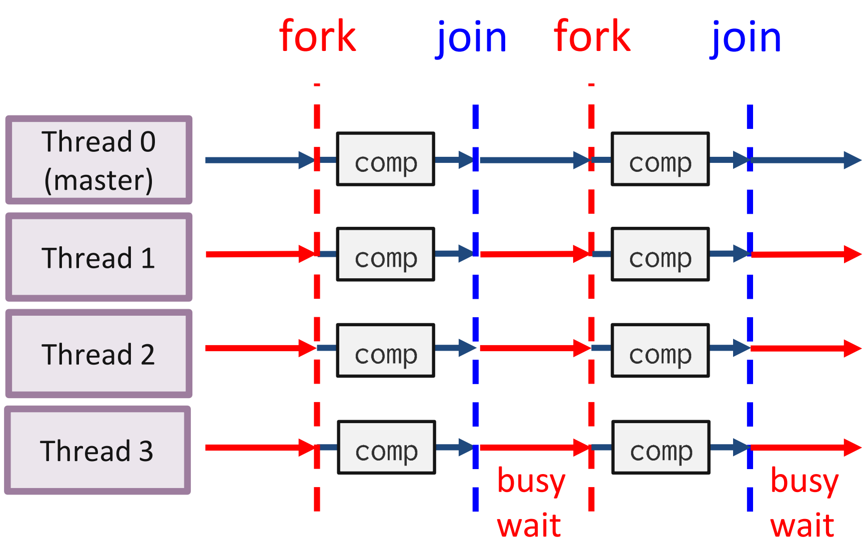
Active Waiting Policy for Flat Parallelism

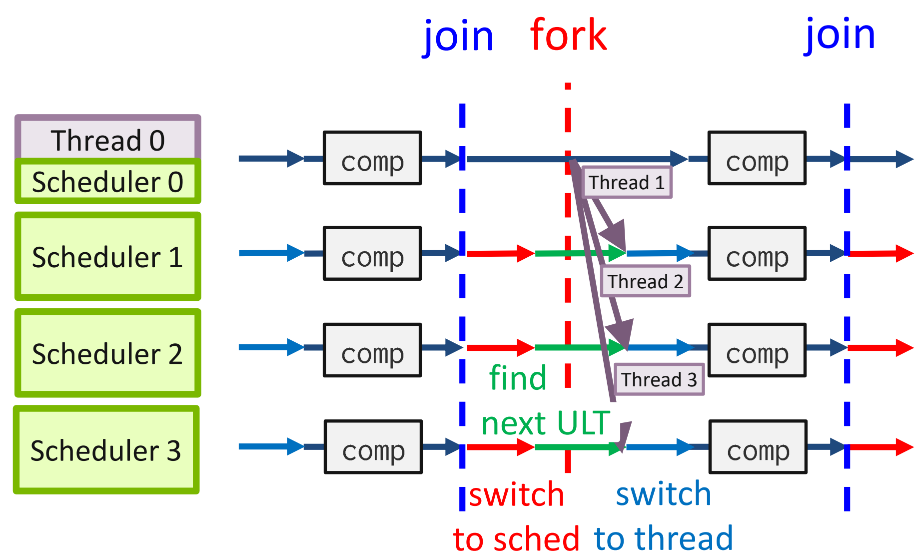
```
for (int iter = 0; iter < n; iter++) {
  #pragma omp parallel for num_threads(4)
  for (int i = 0; i < 4; i++)
    comp(i);
}
```

- Active waiting policy improves performance of flat parallelism by busy-wait based synchronization.

```
OMP_WAIT_POLICY
 =<active/passive>
```

- If active, Pthreads-based OpenMP busy-waits for the next parallel region.
- BOLT on the other hand yields to a scheduler on fork-and-join (~ passive).





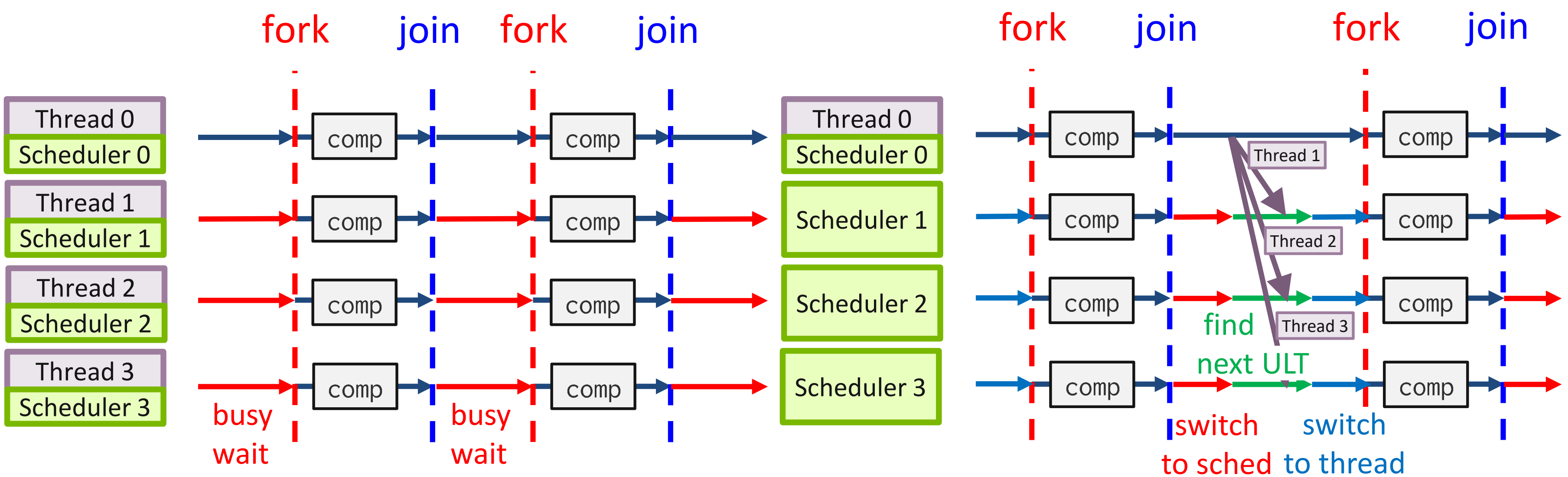
* If passive, after completion of work, threads sleep on a condition variable.

Busy wait is faster than lightweight user-level context switch!

Implementation of Active Policy in BOLT

New?

- If active, busy-waits for next parallel regions.
- If passive, relies on ULT context switching.

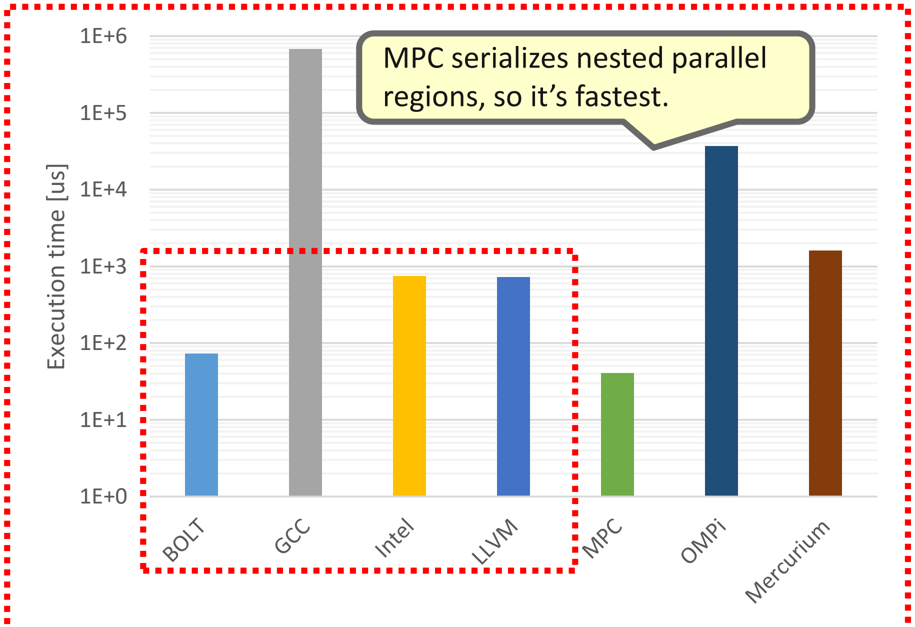


ULT threads are not preemptive, so BOLT periodically yields to a scheduler in order to avoid the deadlock (especially when # of OpenMP threads > # of schedulers).

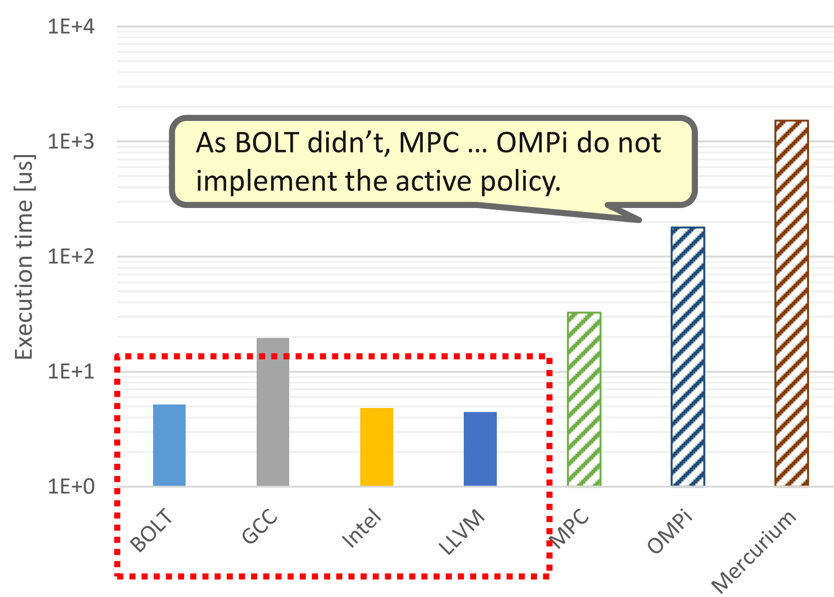
Performance of Flat and Nested

```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++) no_comp(i, j);
```

```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  no_comp(i);
```



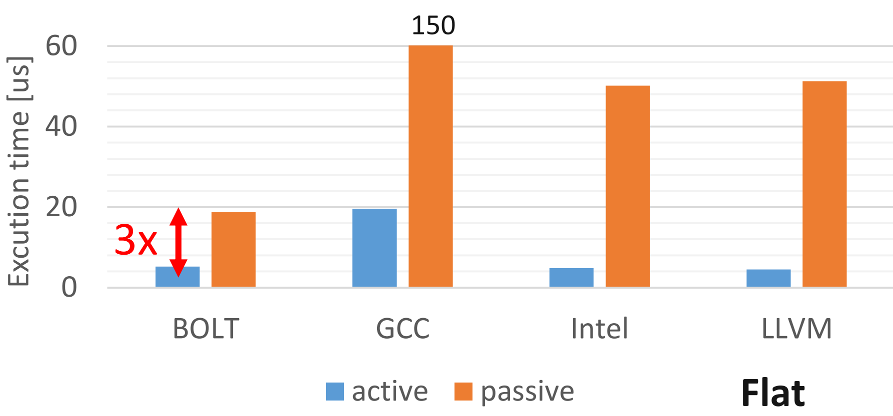
Nested (passive)

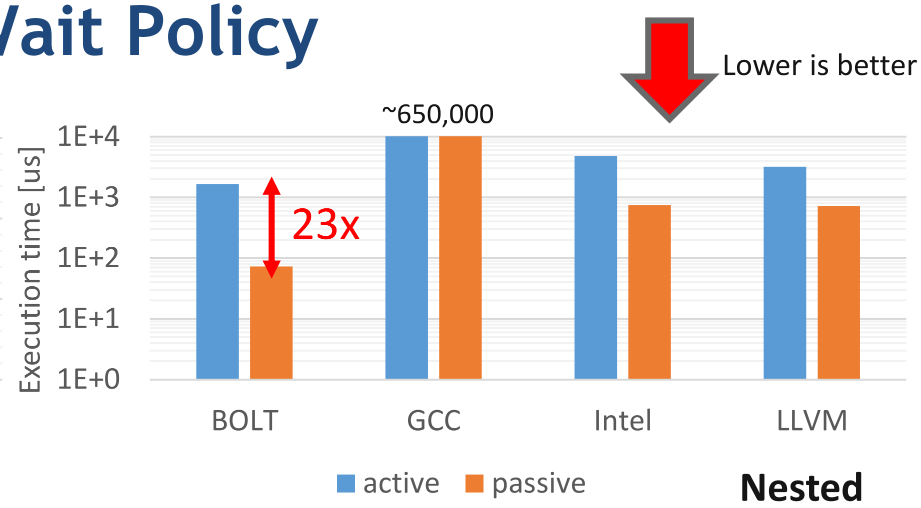


Flat (active)

Lower is better

Penalty of the Opposite Wait Policy






```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++) no_comp(i, j);
```

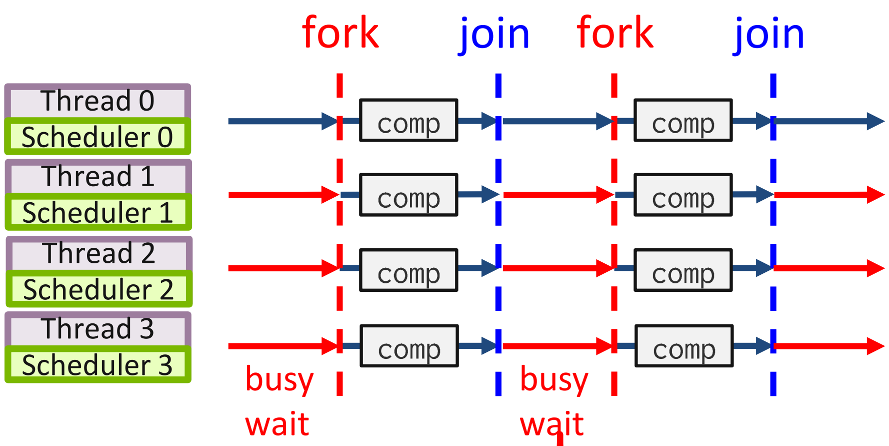
```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  no_comp(i);
```

- How to coordinate threads significantly affects the overheads.
  - Large performance penalty discourages users from enabling nesting.

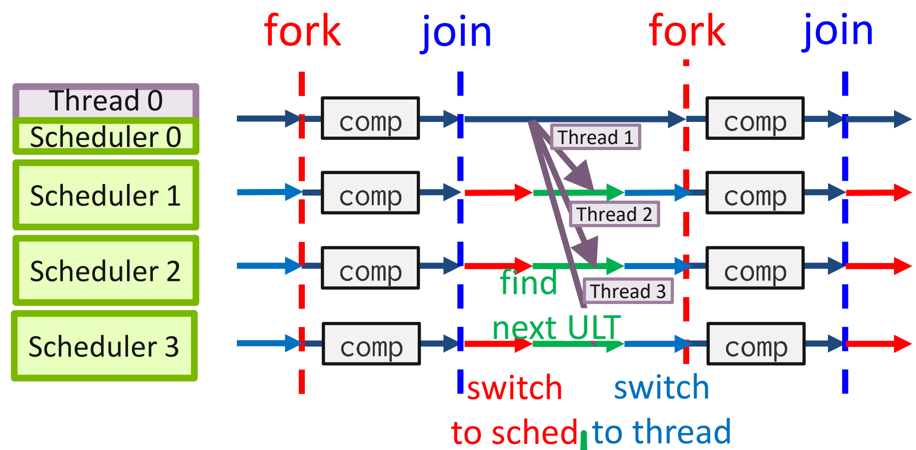
- Is there a good algorithm to transparently support both flat and nested parallelism?

Busy Waiting in Both Active/Passive Algorithms

BOLT (active)



BOLT (passive)

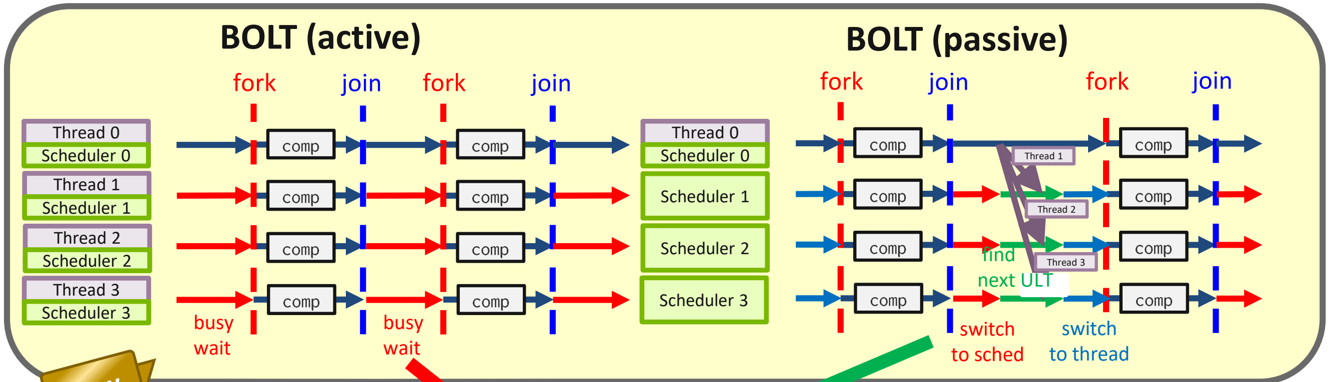


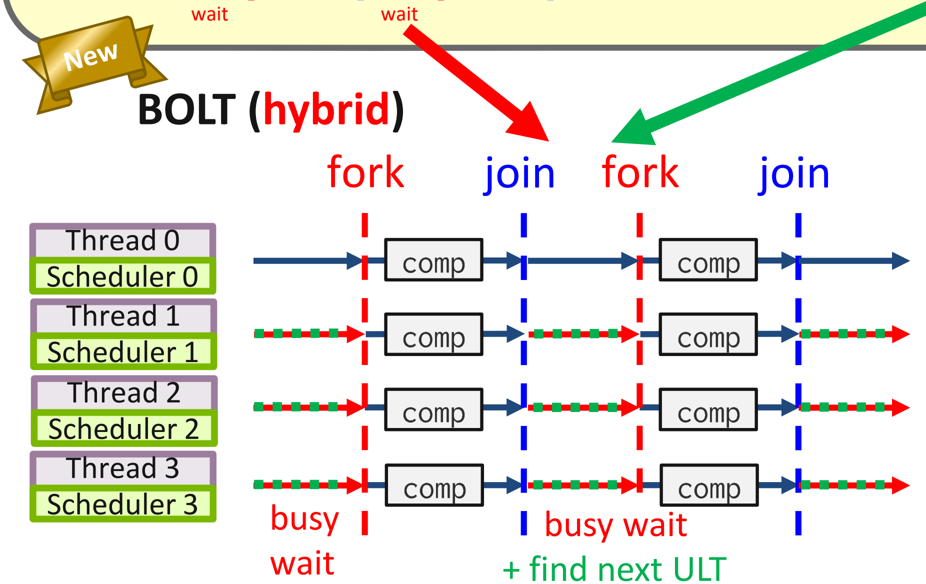

```
void omp_thread() {
RESTART_THREAD:
  comp();
  while (time_elapsed() < KMP_BLOCKTIME) {
    if (team->next_parallel_region_flag)
      goto RESTART_THREAD;
  }
}
```

```
void user_scheduler() {
  while (1) {
    ULT_t *ult = get_ULT_from_queue();
    if (ult != NULL)
      execute(ult);
  }
}
```

- Though in both active and passive cases, they enter busy-waits after the completion of threads.
  - Can we merge it to perform both scheduling and flag checking?

Algorithm: Hybrid Wait Policy





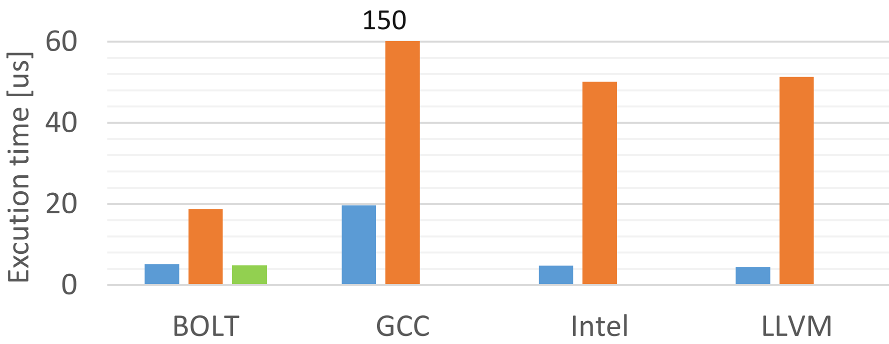

```
void omp_thread() {
RESTART_THREAD:
  comp();
  while (time_elapsed() < KMP_BLOCKTIME) {
    if (team->next_parallel_region_flag)
      goto RESTART_THREAD;
    ULT_t *ult = get_ULT_from_queue
                 (parent_scheduler);
    if (ult != NULL)
      return_to_sched_and_run(ult);
  }
}
```

This technique is not applicable to OS-level threads since the scheduler is not revealed.

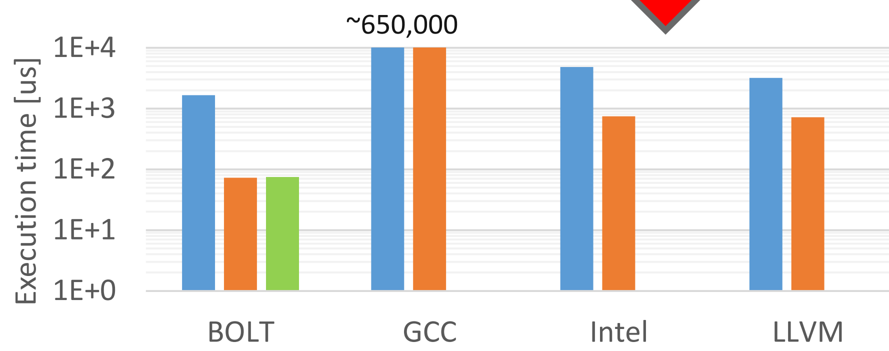
- Hybrid: execute flag check and queue check alternately.
  - [flat]: a thread does not go back to a scheduler.
  - [nested]: another available ULT is promptly scheduled.

Performance of Hybrid: Flat and Nested

Lower is better



Flat

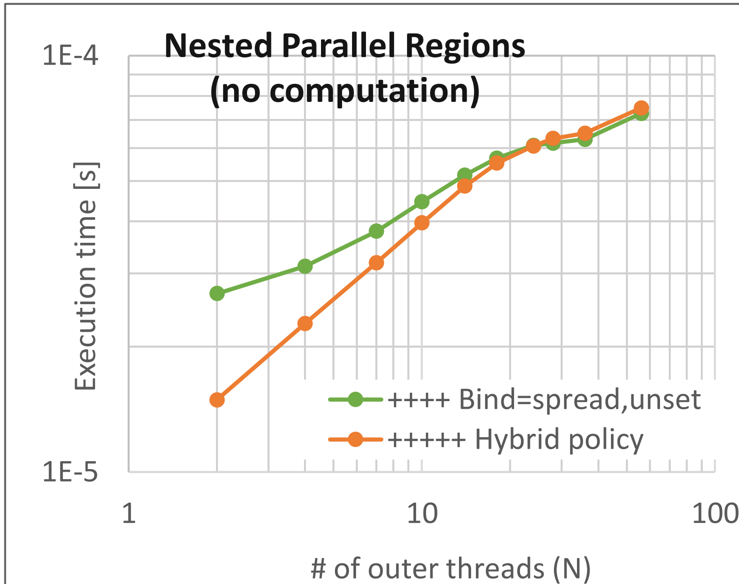


Nested

```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++) no_comp(i, j);
```

```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  no_comp(i);
```

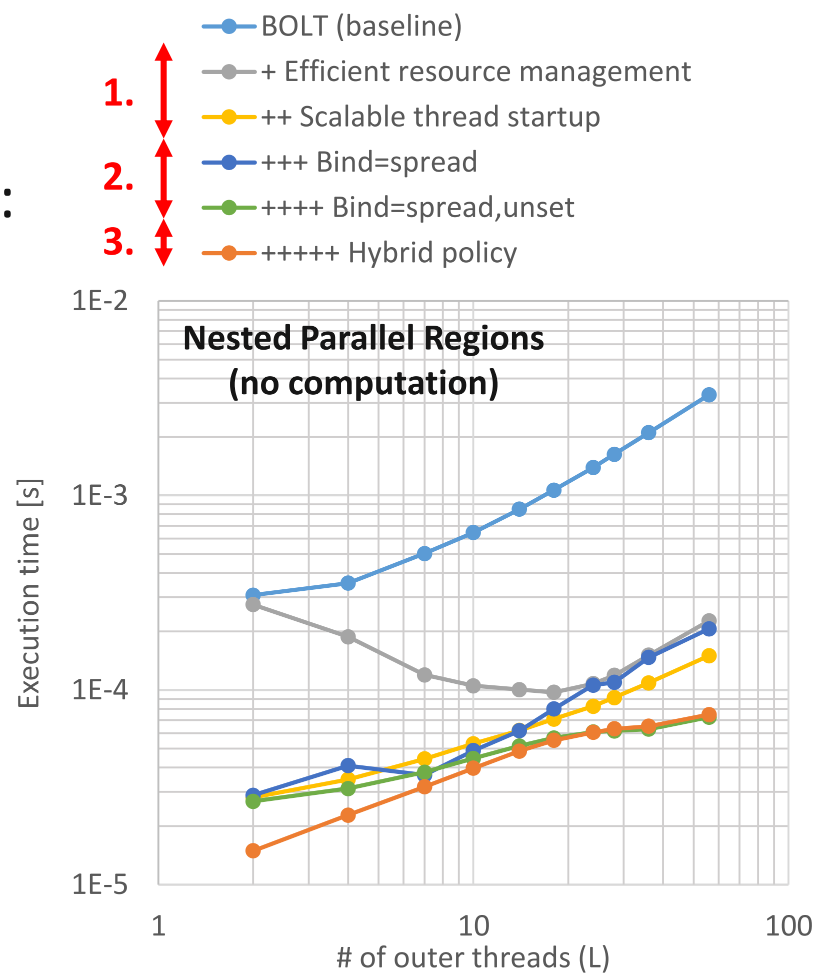
- BOLT (hybrid wait polocy) is always most efficient in both flat and nested cases.
  - We suggest a new keyword “auto” so that the runtime can choose the implementation.



Summary of the Design

- Just using ULT is insufficient.
  => Three kinds of optimizations:
  1. Address scalability bottlenecks
  2. ULT-friendly affinity
  3. Hybrid wait policy for
     flat and nested parallelisms

```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(L)
for (int i = 0; i < L; i++)
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++)
    no_comp();
```



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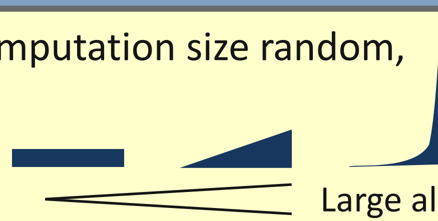
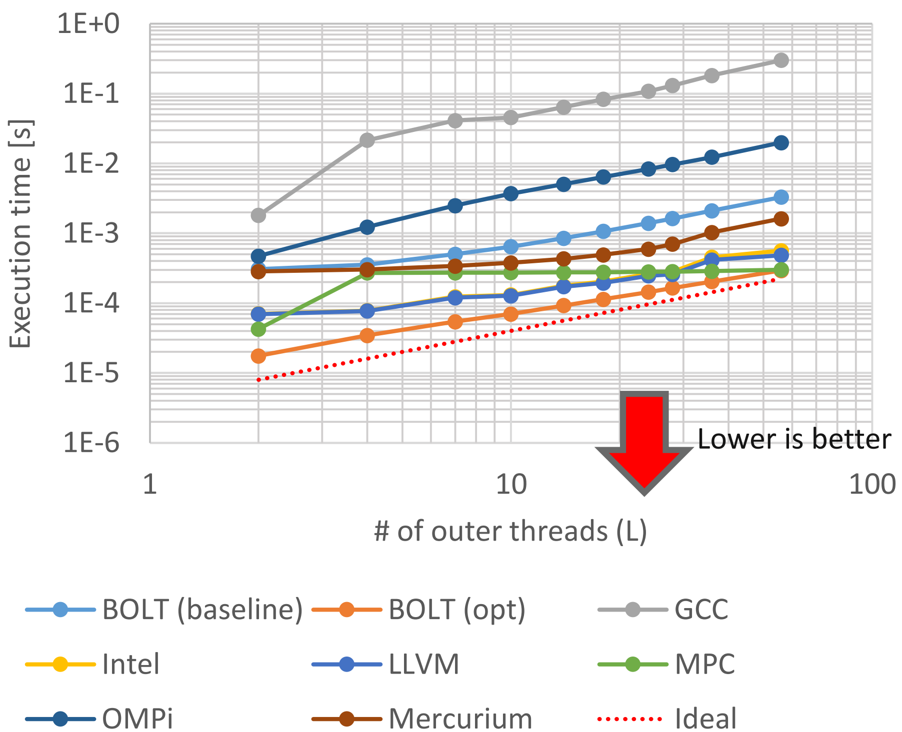
Microbenchmarks

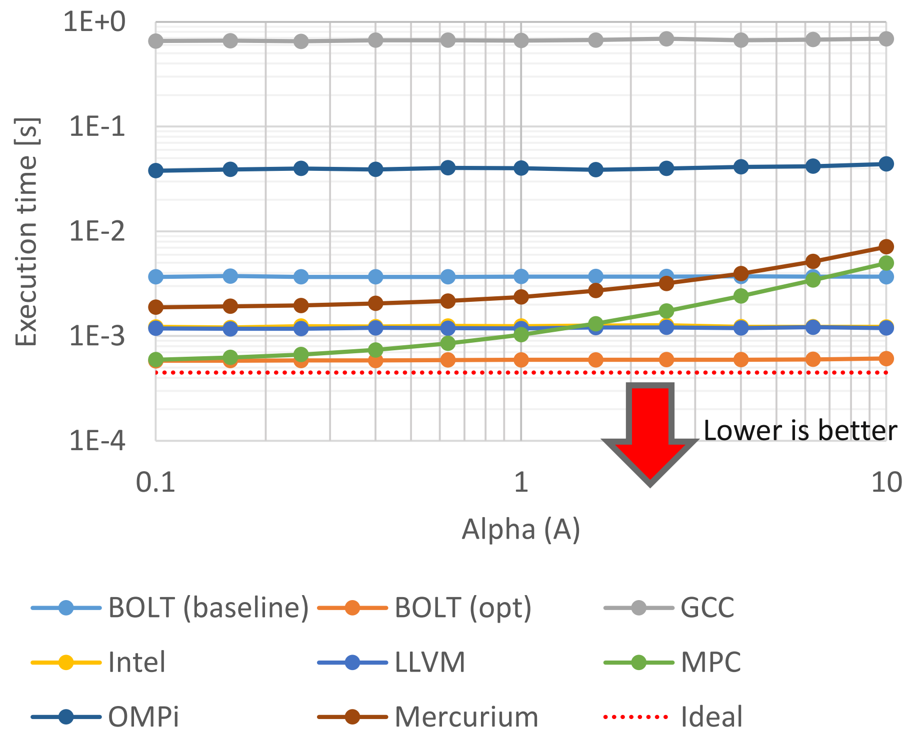
alpha makes the computation size random, while keeping the total problem size.




```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(L)
for (int i = 0; i < L; i++) {
  #pragma omp parallel for num_thLreads(28)
  for (int j = 0; j < 28; j++)
    comp_20000_cycles(i, j);
}
```

```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++) {
  int work_cycles = get_work(i, alpha);
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++)
    comp_cycles(i, j, work_cycles);}
```



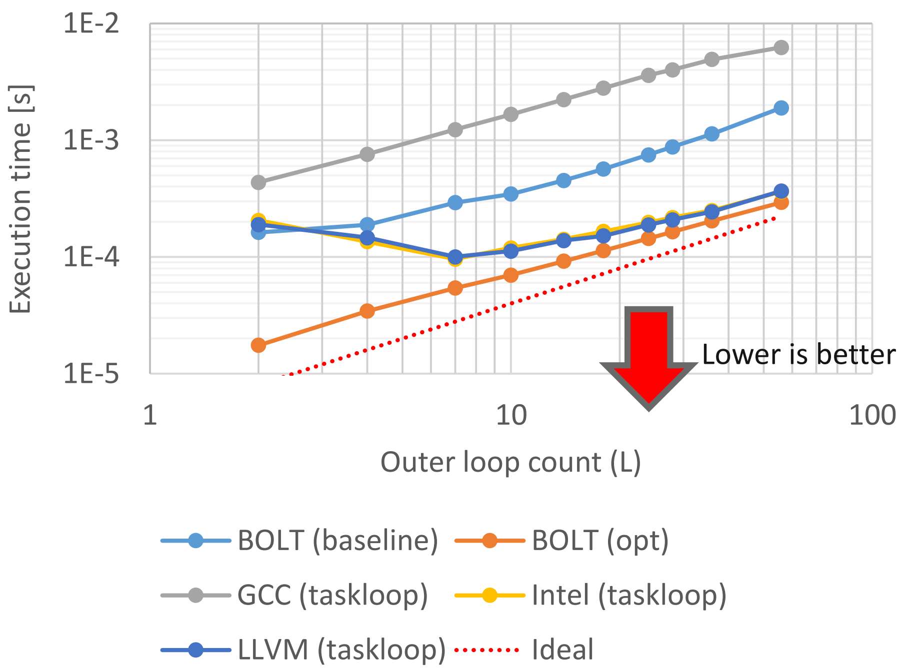


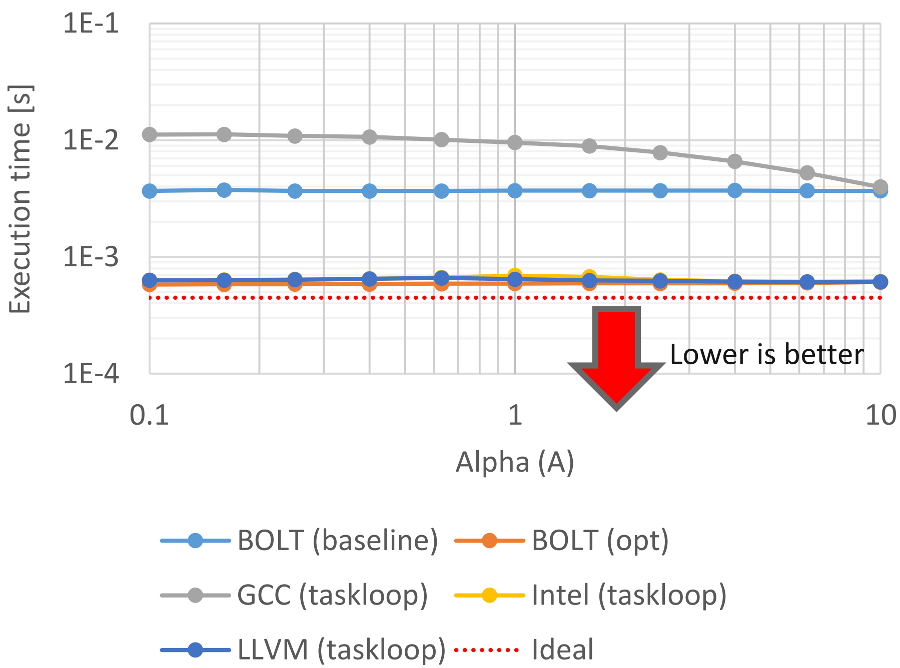
(Ideal): theoretical lower bound under perfect scalability.

Microbenchmarks: vs. taskloop

```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(56)
for (int i = 0; i < L; i++) {
  #pragma omp taskloop grainsize(1)
  for (int j = 0; j < 28; j++)
    comp_20000_cycles(i, j);
}
```

```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++) {
  int work_cycles = get_work(i, alpha);
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++)
    comp_cycles(i, j, work_cycles);}
```

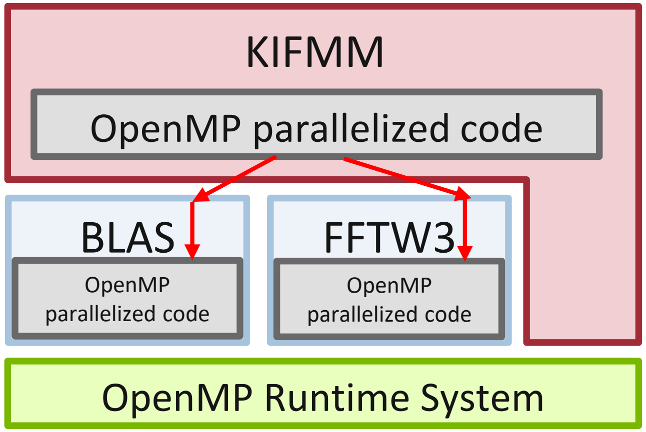




- Parallel regions of BOLT are as fast as taskloop!

Evaluation: KIFMM

- KIFMM[*]: highly optimized N-body solver
  - N-body solver is one of the heaviest kernels in astronomy simulations.
- Multiple layers are parallelized by OpenMP.
  - BLAS and FFT.
- We focus on the upward phase in KIFMM.

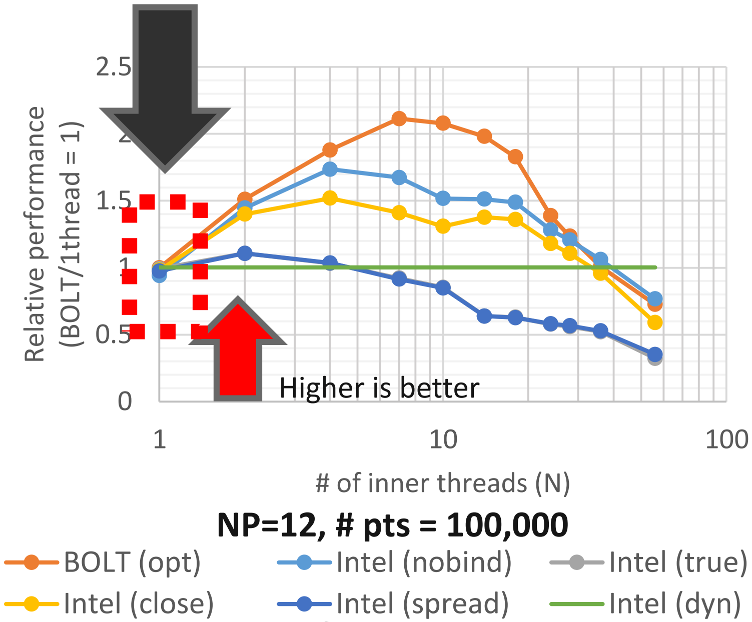



```
for (int i = 0; i < max_levels; i++)
  #pragma omp parallel for
  for (int j = 0; j < nodecounts[i]; j++) {
    [...];
    dgemv(...); // dgemv() creates a parallel region.
  }
```

[*] A. Chandramowlishwaran et al., "Brief Announcement: Towards a Communication Optimal Fast Multipole Method and Its Implications at Exascale", SPAA '12, 2012

Performance: KIFMM

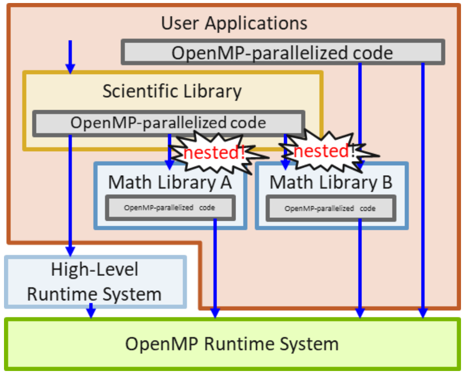
```
void kifmm_upward():
  for (int i = 0; i < max_levels; i++)
    #pragma omp parallel for num_threads(56)
    for (int j = 0; j < nodecounts[i]; j++) {
      [...];
      dgemv(...); // creates a parallel region.
    }

void dgemv(...): // in MKL
  #pragma omp parallel for num_threads(N)
  for (int i = 0; i < [...]; i++)
    dgemv_sequential(...);
```



Different Intel OpenMP configurations:
nobind(=false),true,close,spread: proc_bind
dyn: MKL_DYNAMIC=true
Note that other parameters are hand tuned (see the paper).

- Experiments on Skylake 56 cores.
  - # of threads for the outer parallel region = 56
  - # of threads for the inner parallel region = N (changed)
- Two important results:
  - N=1 (flat): performance is almost the same.
  - N>1 (nested): BOLT further boosts performance.

Summary: ULT-based OpenMP Threads

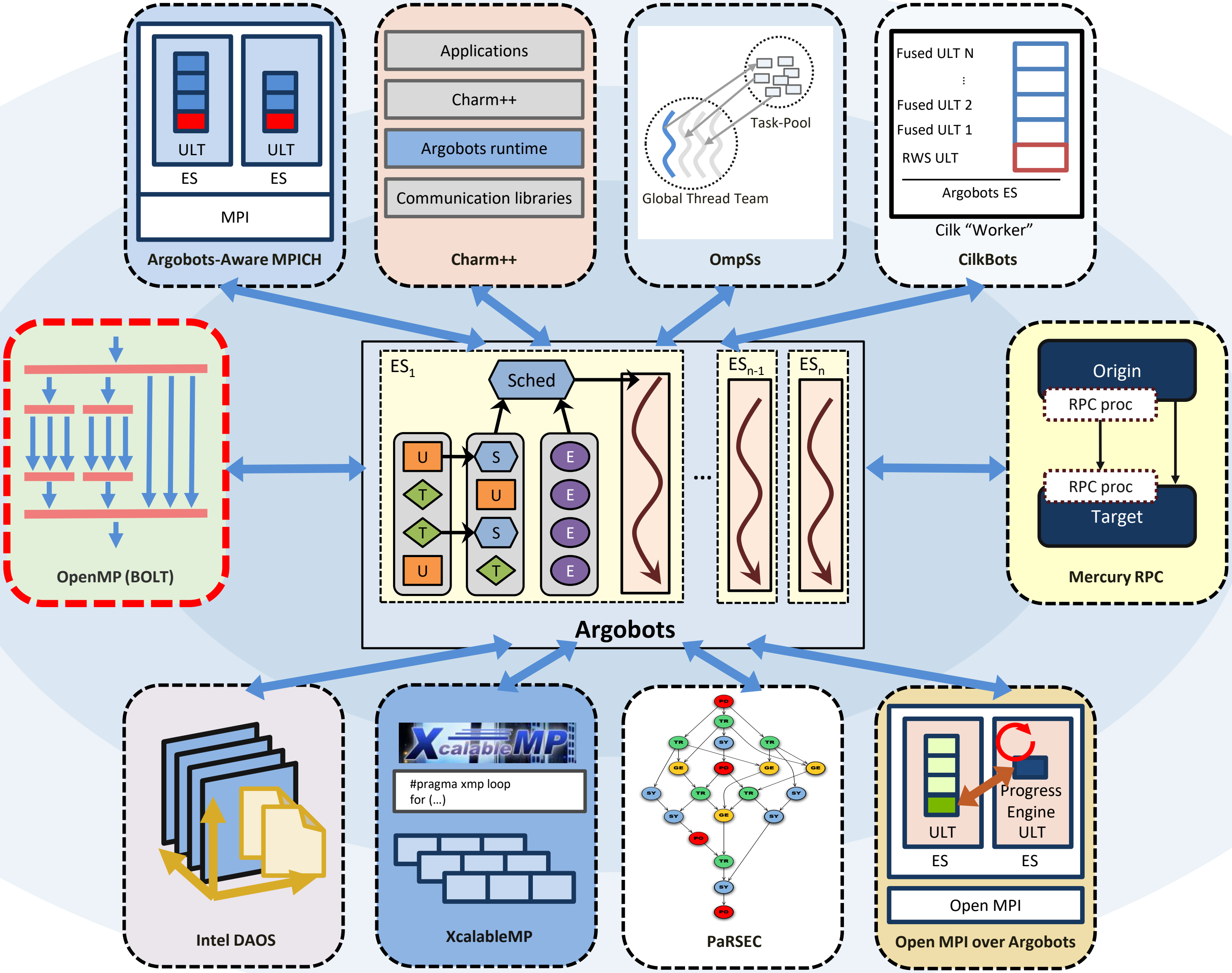


- Nested OpenMP parallel regions are commonly seen in complicated software stacks.
  => Demand for efficient OpenMP runtimes
  to exploit both flat and nested parallelism.
- BOLT: an lightweight OpenMP library over ULT.
  - Simply using ULTs is insufficient:
    - Solve scalability bottlenecks in the LLVM OpenMP runtime
    - ULT-friendly affinity implementation
    - Hybrid thread coordination technique to transparently support both flat and nested parallel regions.
- BOLT achieves unprecedented performance for nested parallel regions without hurting the performance of flat parallelism.

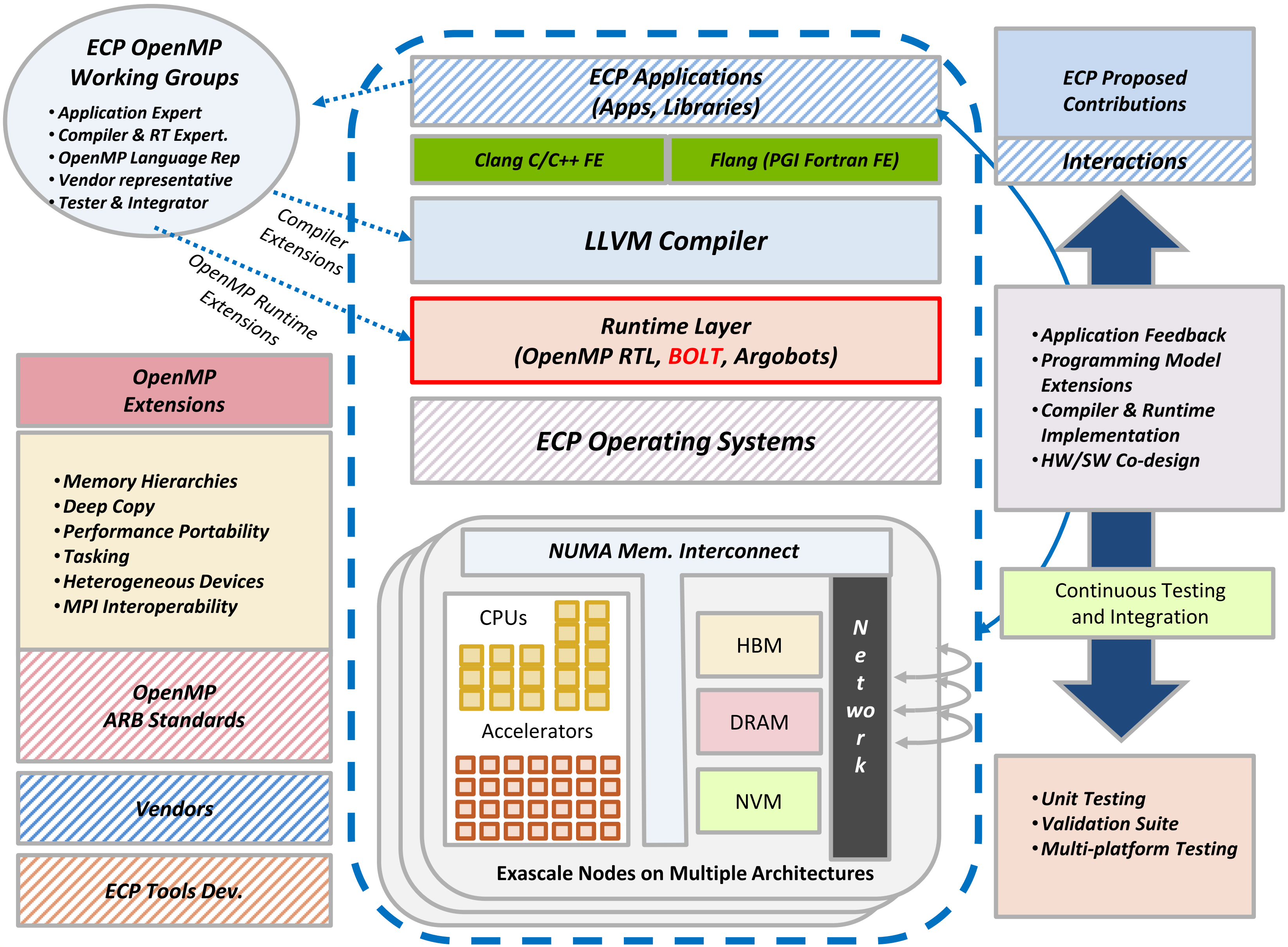
Index

1. BOLT is OpenMP over lightweight threads
   - What is a user-level thread (ULT)?
2. User-level threads for OpenMP threads
   - Nested parallel regions and issues
   - Efficient adoption of ULTs
   - Evaluation
3. User-level threads for OpenMP tasks
   - OpenMP task and MPI operations
   - Tasking over ULT-aware MPI
4. **Conclusions and future work**

Argobots Ecosystem



BOLT in ECP SOLLVE



How to Build BOLT?

1. Use the latest version (https://github.com/pmodels/bolt)
   - Please follow the instruction.

```
git clone https://github.com/pmodels/bolt.git $BOLT_DIR
cd $BOLT_DIR
## to use the very latest version:
# git checkout latest
git submodule update --init
mkdir build && cd build
cmake ../ -DCMAKE_INSTALL_PREFIX=BOLT_INSTALL_DIR \
  -DCMAKE_BUILD_TYPE=Release -DLIBOMP_USE_ARGOBOTS=on
make -j install
```

2. Use Spack (https://github.com/spack/spack)

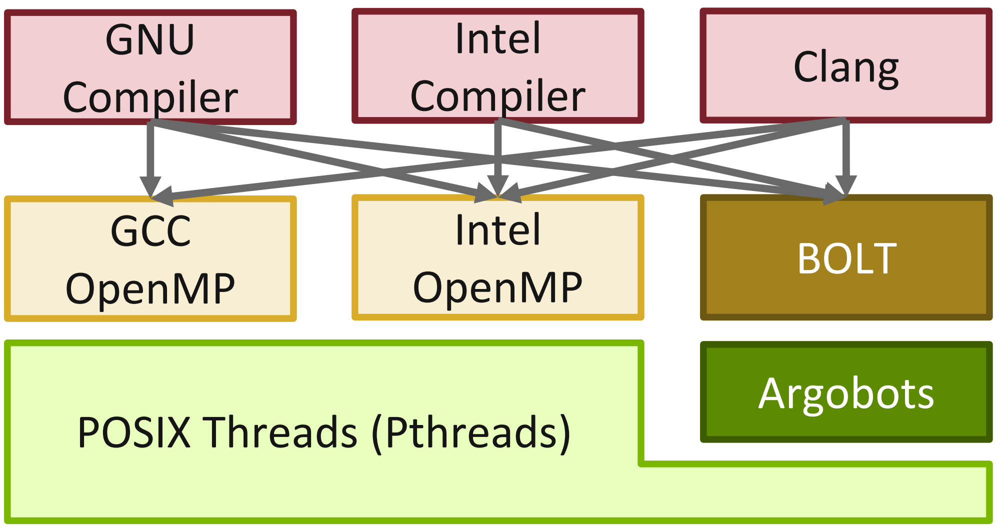
```
spack install bolt
```

BOLT: High Compatibility with Existing Libraries

- BOLT keeps compatibility with the LLVM OpenMP interface.
  - Several compilers (GCC, Intel Compilers, and Clang/LLVM) can be used as a frontend.
    - i.e., BOLT does not require a special compiler.

```
# app is compiled for GCC or Intel OpenMP
# run app over a default OpenMP library
./app arg1 arg2 ...
```

```
# run app over BOLT
LD_LIBRARY_PATH=$BOLT_INSTALL_PATH \
./app arg1 arg2 ...
```



  - No need to recompile existing applications and libraries for BOLT!

Note: some existing proposals require special compilers.

How to Use BOLT?

- ***No recompilation needed. Just change the runtime library.***
- [Recommended] Set LD_LIRBARY_PATH

```
$ LD_LIBRARY_PATH=“$BOLT/install/lib:${LD_LIBRARY_PATH}” ./prog
```

  - Please check if BOLT is loaded by **ldd**:

```
$ LD_LIBRARY_PATH=“$BOLT/install/lib:${LD_LIBRARY_PATH}” ldd ./prog
linux-vdso.so.1 =>  (0x00007fff3bbbe000)
libm.so.6 => /lib64/libm.so.6 (0x00007f6e9fc29000)
libiomp5.so => /home/user/bolt/install/lib/libiomp5.so
(0x00007f6e9f994000)
```

If you cannot find it, LD_LIBRARY_PATH does not work. It often happens if you use GCC as a frontend.

- [Fallback] Set LD_PRELOAD

```
# GCC
$ LD_PRELOAD=“$BOLT/install/lib/libgomp.so:${LD_PRELOAD}” ./prog
# Intel C/C++ Compilers
$ LD_PRELOAD=“$BOLT/install/lib/libiomp5.so:${LD_PRELOAD}” ./prog
# Clang/LLVM
$ LD_PRELOAD=“$BOLT/install/lib/libomp.so:${LD_PRELOAD}” ./prog
```

BOLT: Supported Features

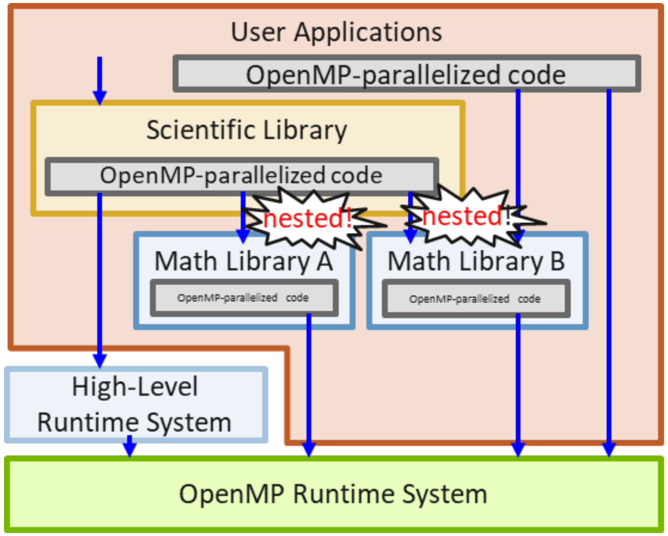
- BOLT supports OpenMP 4.5 with a few exceptions.
  - As the original LLVM OpenMP supports.

The very latest OpenMP 5.0 was released last November. Not yet fully supported.

- BOLT support includes …
  - Basic parallel regions (parallel for/section)
  - Tasks: task, taskloop, task depend
  - Target offloading: (e.g., offload computation to a GPU device)
    - BOLT does not affect the GPU performance
  - Synchronization: single/master/barrier/order, omp_lock
  - SIMD directives: supported by compilers
- BOLT currently does not support …
  - OMPT & OMPD (though they are OpenMP 5.0 features)
  - Task cancellation

Thank You for Listening!

- BOLT[*]: an lightweight OpenMP library over Argobots.
  - BOLT achieves unprecedented performance for nested parallel regions without hurting the performance of flat parallelism.



- It is available at GitHub / Spack
  1. BOLT repository (https://github.com/pmodels/bolt)
  2. Spack (https://github.com/spack/spack)

```
spack install bolt
```


Acknowledgment

This research was supported by the Exascale Computing Project (17-SC-20-SC), a joint project of the U.S. Department of Energy's Office of Science and National Nuclear Security Administration, responsible for delivering a capable exascale ecosystem, including software, applications, and hardware technology, to support the nation's exascale computing imperative.

[*] S. Iwasaki et al., "BOLT: Optimizing OpenMP Parallel Regions with User-Level Threads", PACT '19, 2019