BOLT: Optimizing OpenMP Parallel Regions with User-Level Threads

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OpenMP: the Most Popular Multithreading Model

- Multithreading is essential for exploiting modern CPUs.
- 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

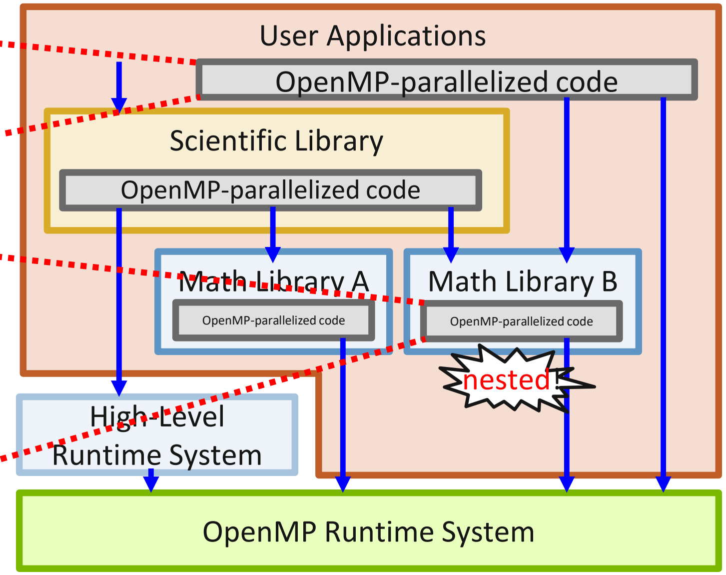
Unintentional Nested OpenMP Parallel Regions

```
#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!

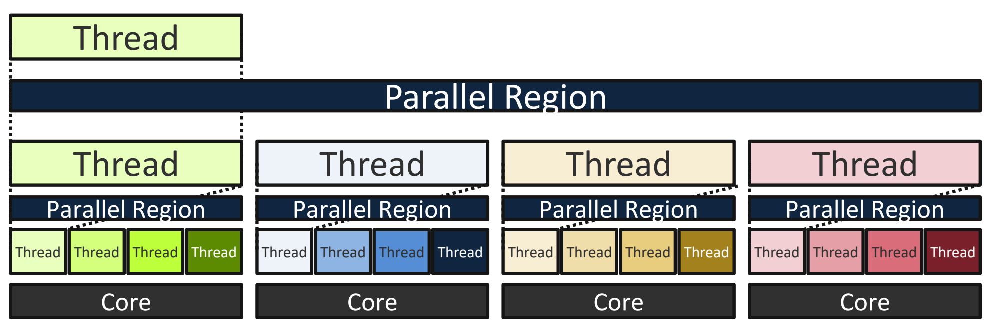
Code Example



- 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++);
```



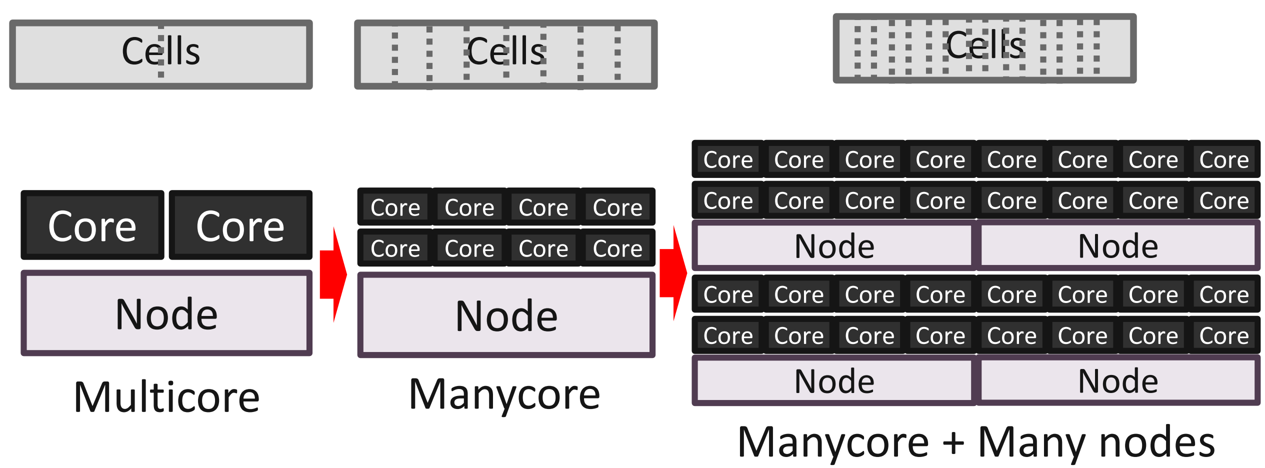
Can We Just Disable Nested Parallelism?

- 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.

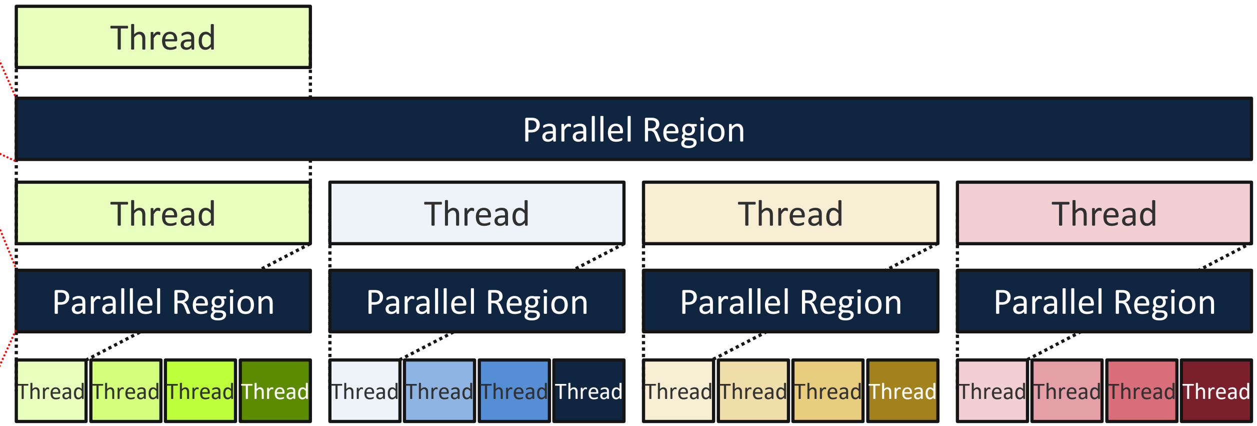
Index

1. Introduction
2. **Existing Approaches**
   - OS-level thread-based approach
   - User-level thread-based approach
     - What is a user-level thread (ULT)?
3. BOLT for both Nested and Flat Parallelism
   - Scalability optimizations
   - ULT-aware affinity (proc_bind)
   - Thread coordination (wait_policy)
4. Evaluation
5. Conclusion

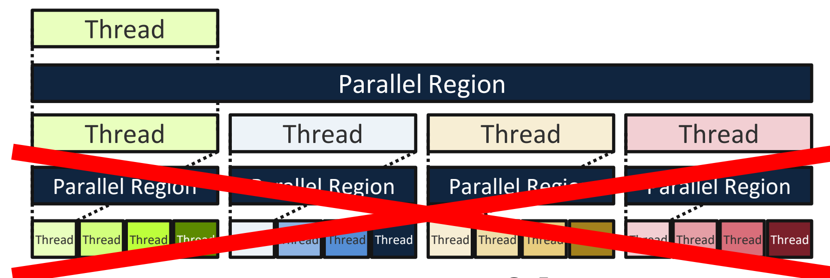
Direction 1: Work around with OS-Level Threads (1/2)

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

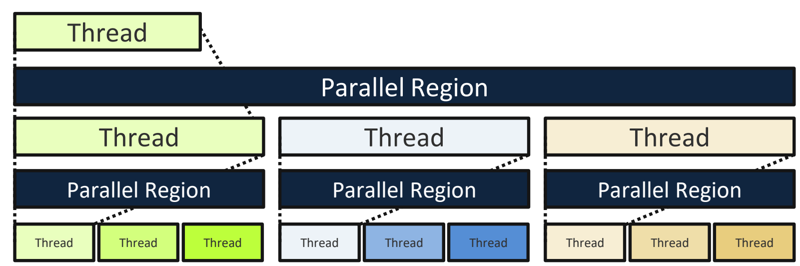
```
// BLAS library
void dgemv(...) {
  #pragma omp parallel for
  for (i = 0; i < n; i++)
    dgemv_seq(data[n], i);
}
```



- 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.



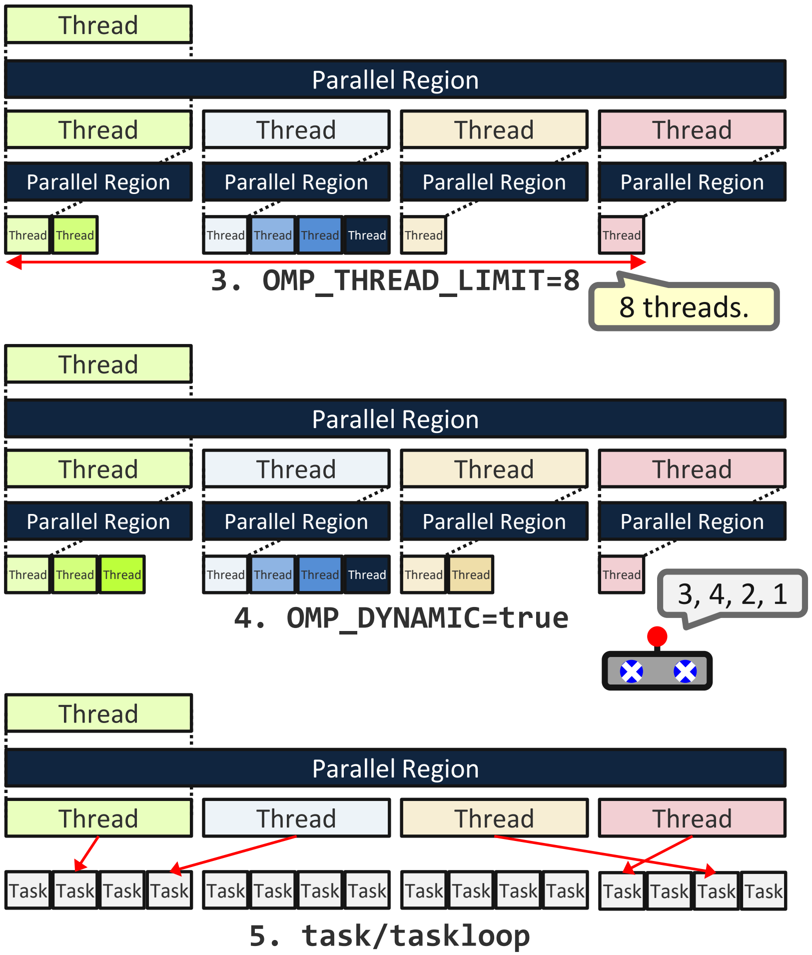
1. `OMP_NESTED=false`



2. `OMP_NUM_THREADS=3,3`

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

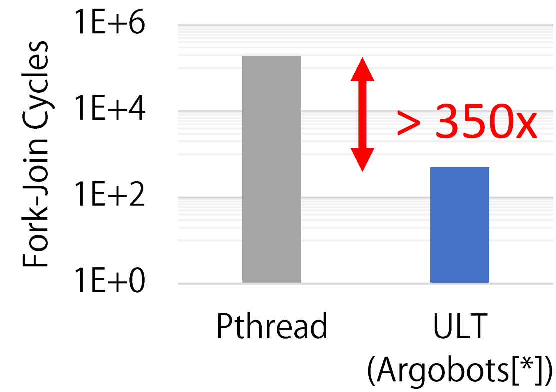
- Workarounds (cont.)
  3. Limit the total number of threads (OMP_THREAD_LIMIT=nths)
     - Can adversely serialize parallel regions; doesn't work well in practice.
  4. Dynamically adjust # of threads (OMP_DYNAMIC=true)
     - Can adversely serialize parallel regions; doesn't work well in practice.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



- How about using lightweight threads for OpenMP threads?

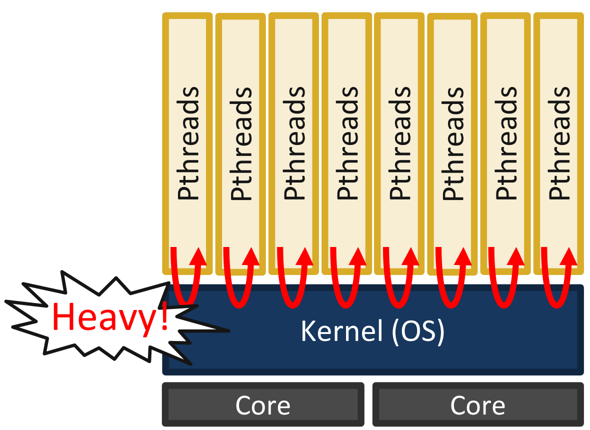
Direction 2: Use Lightweight Threads => User-Level Threads (ULTs)

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



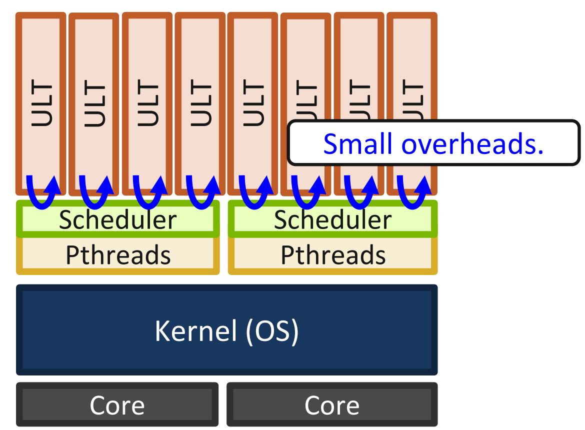
Fork-Join Performance on KNL

Thread scheduling (= context switching) involves heavy system calls.



Naïve Pthreads

User-level threads (ULTs) are running on Pthreads; scheduling is done by user-level context switching in user space.



User-level threads

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

Solution 2: Use User-Level Threads

- The idea of ULTs is not new (back to <90s).

  and more.

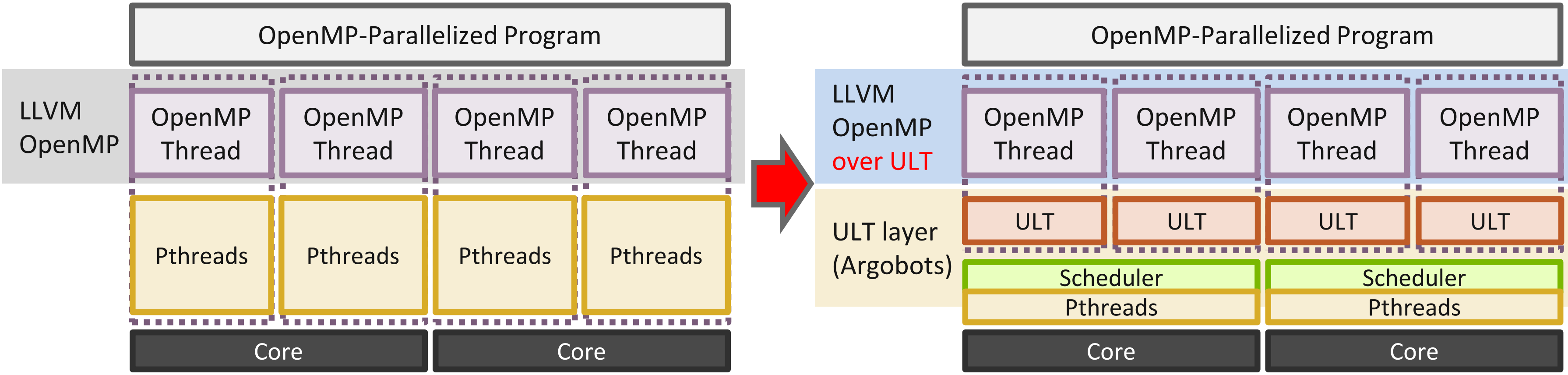
- Several ULT-based OpenMP systems have been proposed.
  - NanosCompiler [1], Omni/ST [2], OMPi [3], MPC [4], ForestGOMP [5], OmpSs (OpenMP compatible mode) [6], LibKOMP [7] …

[1] Marc et al., NanosCompiler: Supporting Flexible Multilevel Parallelism Exploitation in OpenMP. 2000
[2] Tanaka et al., Performance Evaluation of OpenMP Applications with Nested Parallelism. 2000
[3] Hadjidoukas et al., Support and Efficiency of Nested Parallelism in OpenMP Implementations. 2008
[4] Pérache et al., MPC: A Unified Parallel Runtime for Clusters of NUMA Machines. 2008
[5] Broquedis et al., ForestGOMP: An Efficient OpenMP Environment for NUMA Architectures. 2010
[6] Duran et al., A Proposal for Programming Heterogeneous Multi-Core Architectures. 2011
[7] Broquedis et al., libKOMP, an Efficient OpenMP Runtime System for Both Fork-Join and Data Flow Paradigms. 2012

- However, these runtimes do not perform well for several reasons.
  - Lack of OpenMP specification-aware optimizations
  - Lack of general optimizations

For apples-to-apples comparison, we will focus on the ULT-based LLVM OpenMP.

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?

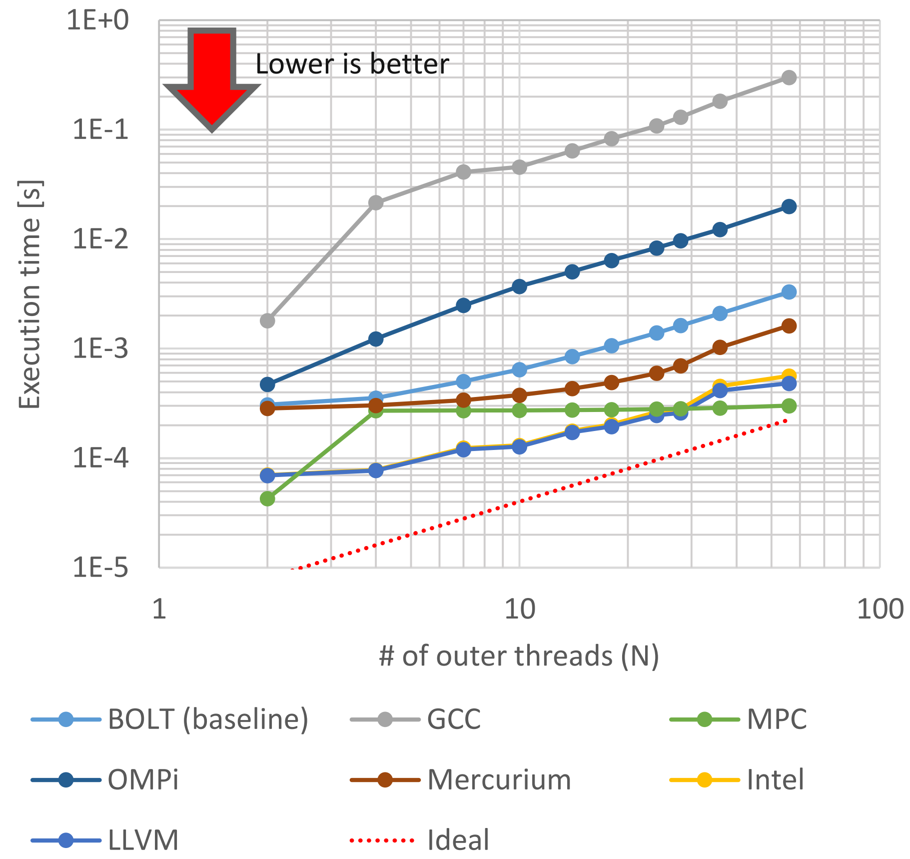
[*] S. Seo et al. "Argobots: A Lightweight Low-Level Threading and Tasking Framework", TPDS '18, 2018

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

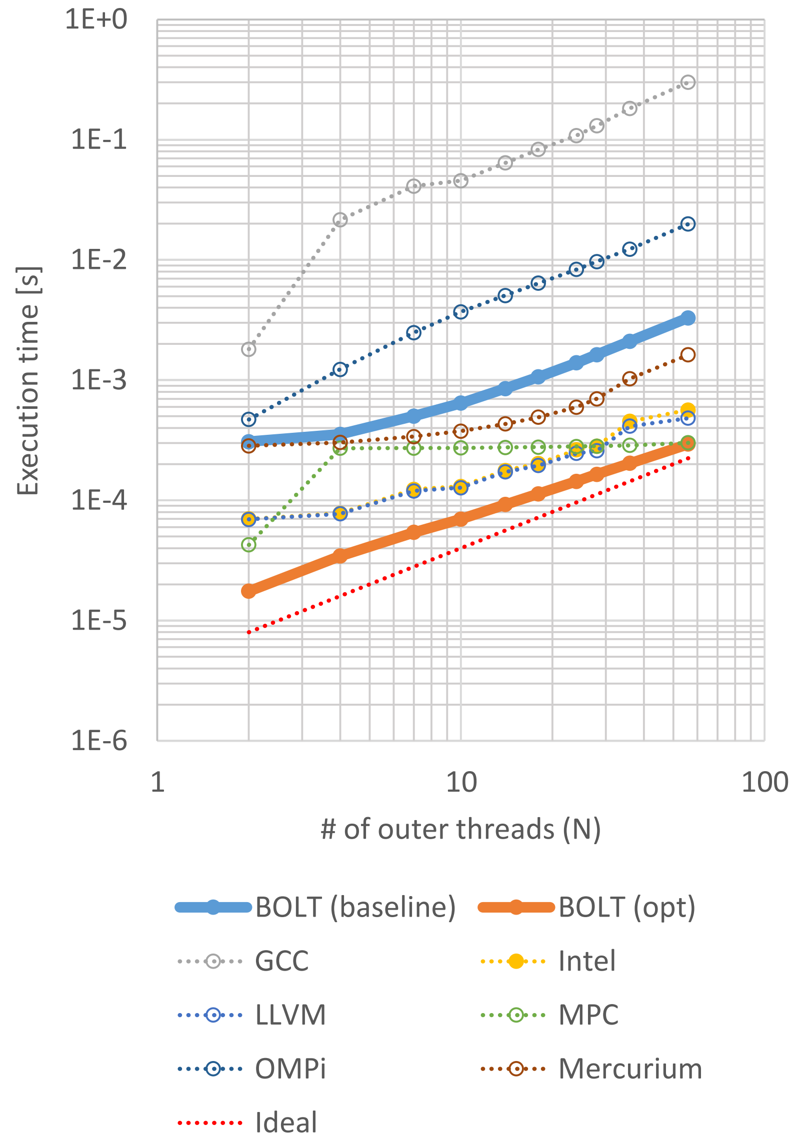
Index

Three Optimization Directions for Further Performance

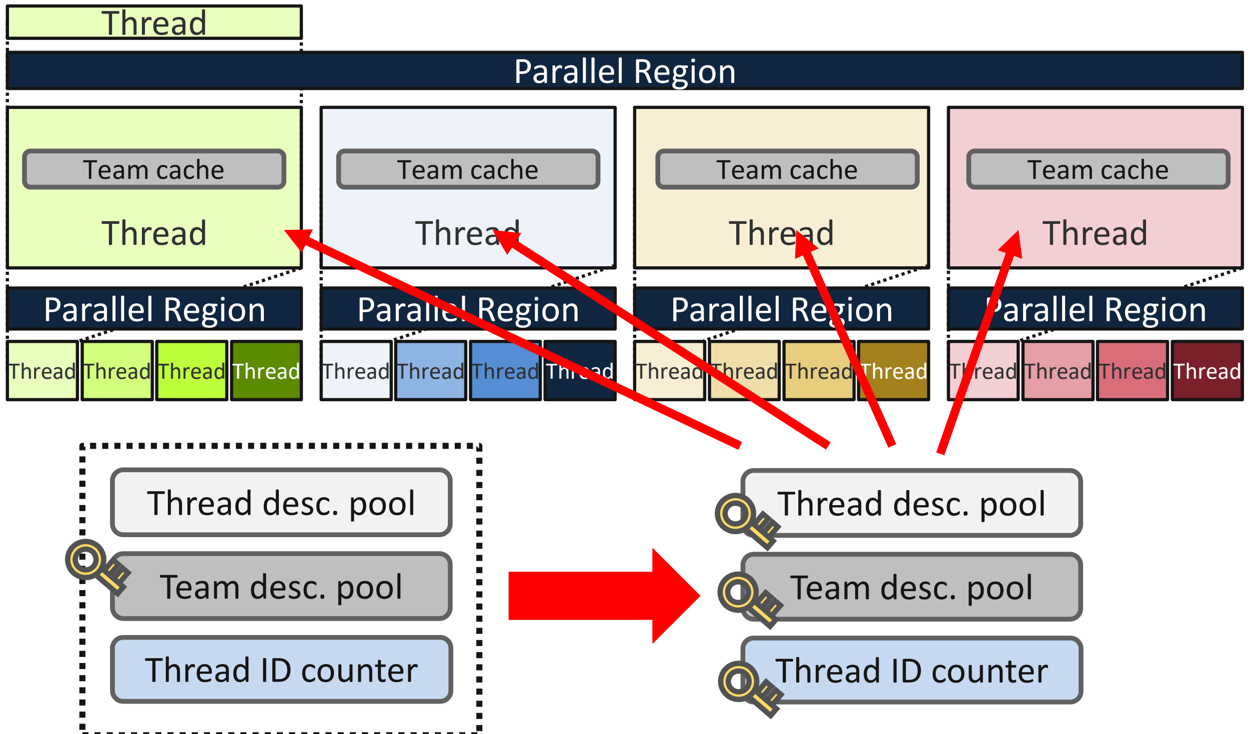
```
// Run on a 56-core Skylake server
#pragma omp parallel for num_threads(N)
for (int i = 0; i < N; i++)
  #pragma omp parallel for num_threads(28)
  for (int j = 0; j < 28; j++)
    comp_20000_cycles(i, j);
```

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



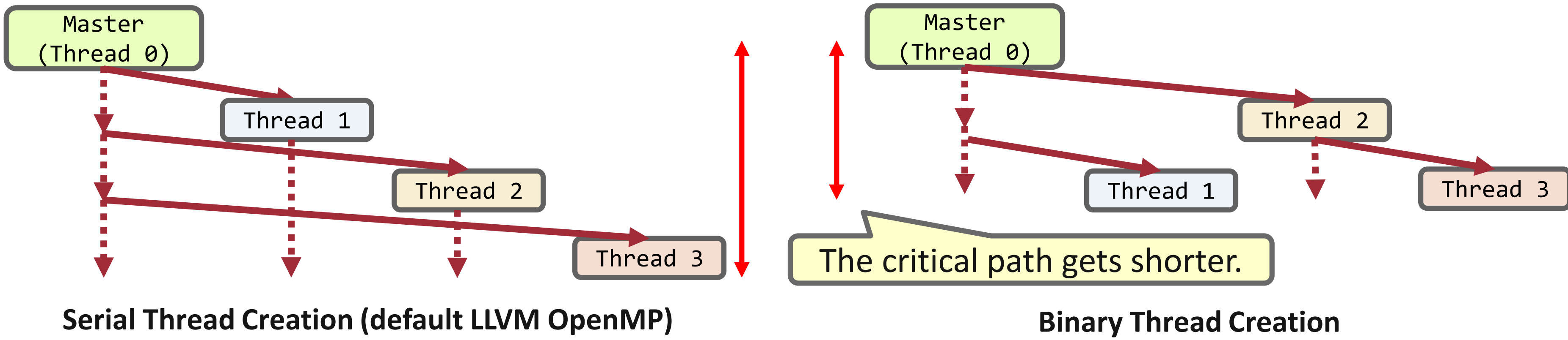
1. Solve Scalability Bottlenecks (1/2)



- 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)

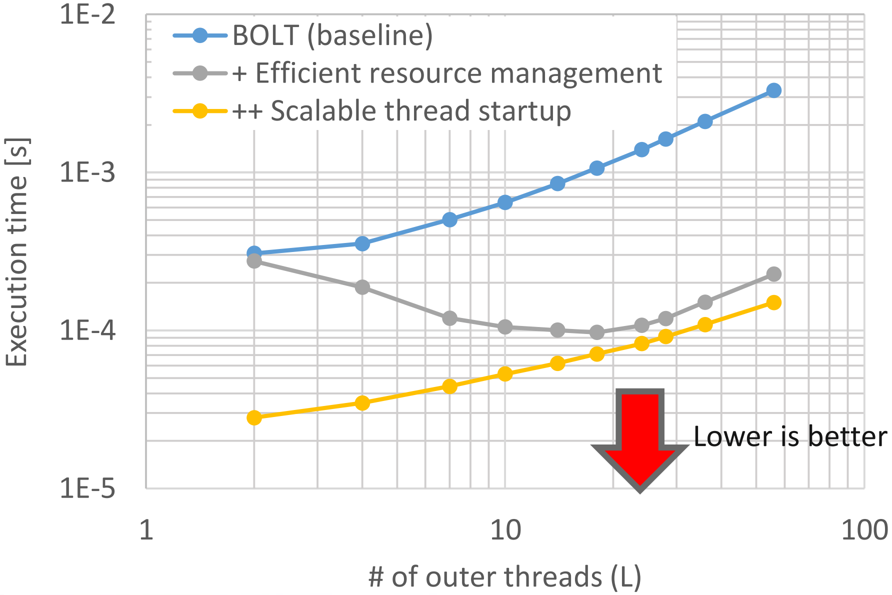
- Thread creation optimizations
  3. Binary creation of OpenMP threads.




```
// 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();
```

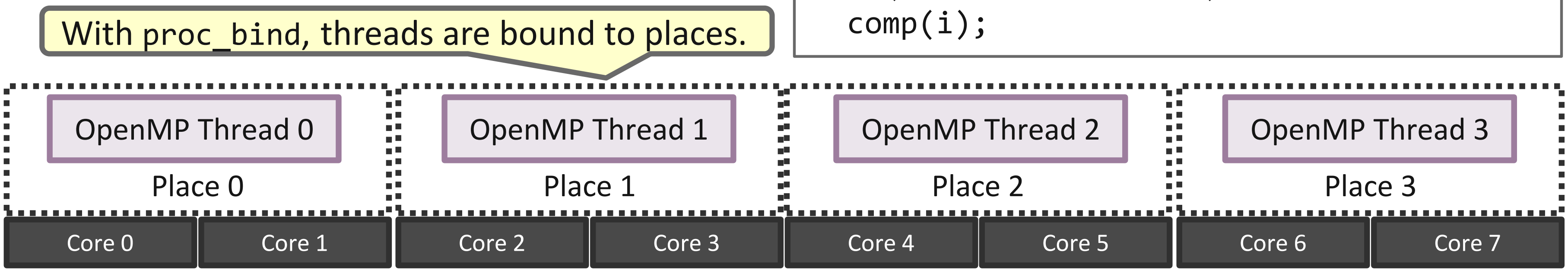
Nested Parallel Regions (no computation)

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);
```

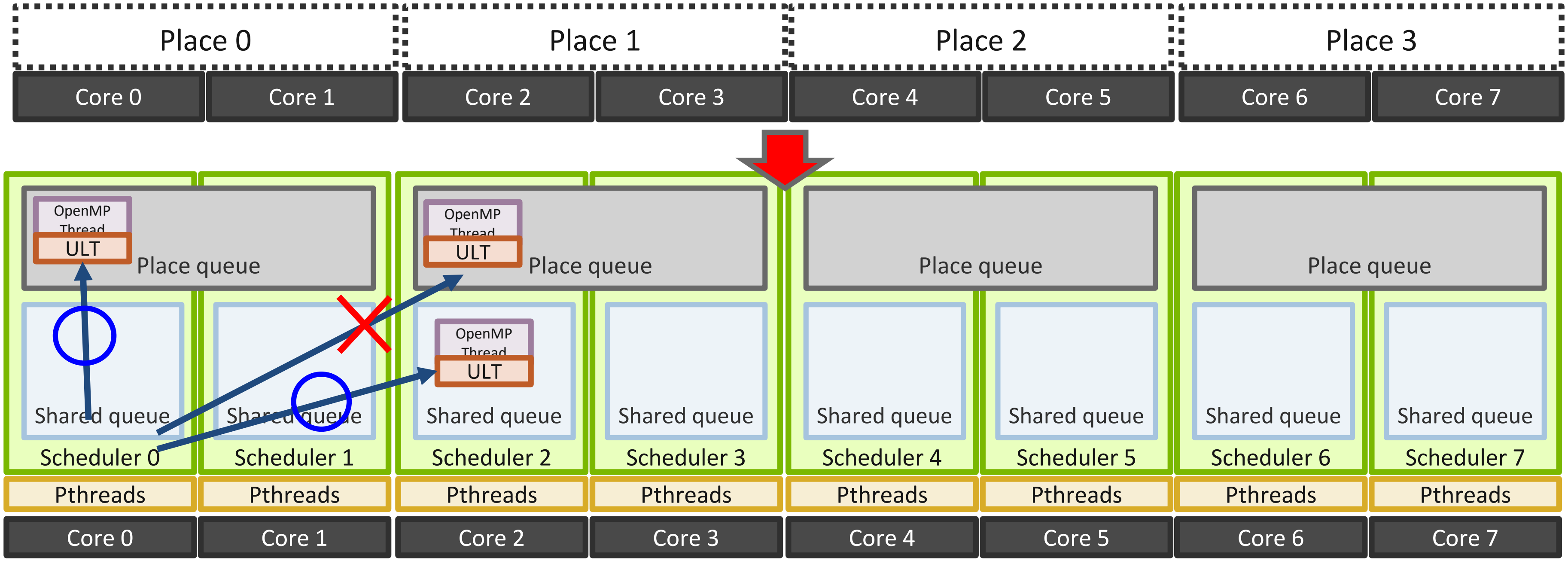


- OpenMP 4.0 introduced *place* and *prod_bind* for affinity.
  - OS-level thread-based libraries (e.g., GNU OpenMP) use CPU masks.
- BOLT (baseline) ignored affinity (still standard compliant).
- However, affinity should be useful to
  1. improve locality and 2. reduce queue contentions.
  - Note: ULT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

Implementation: Place Queue

```
// 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);
```

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



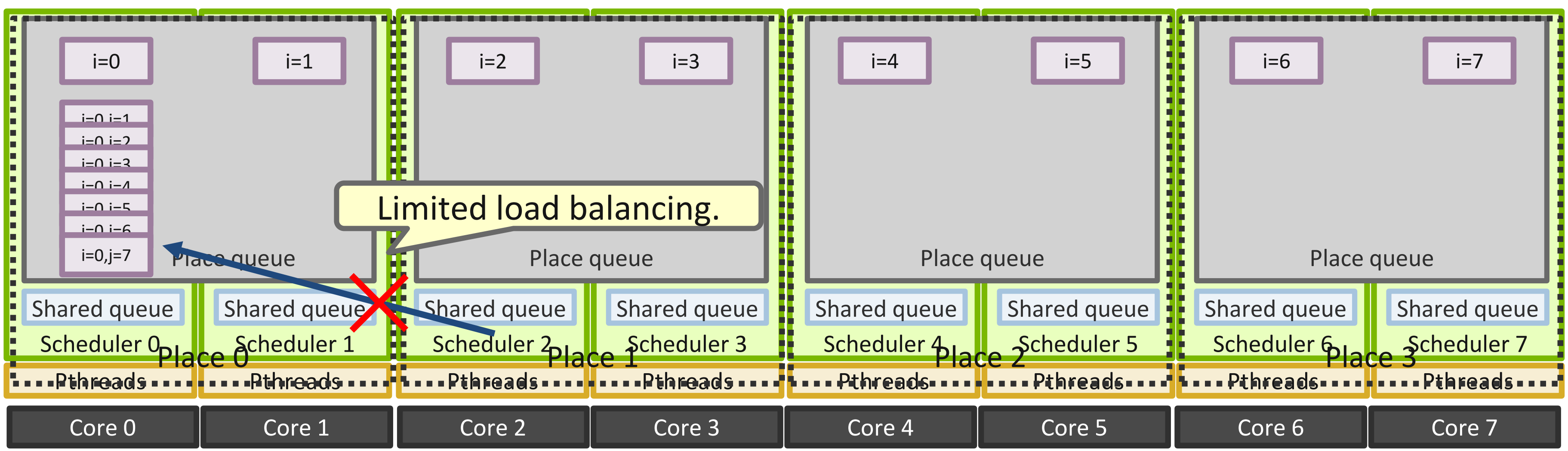
- Problem: OpenMP affinity setting is too deterministic.

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.

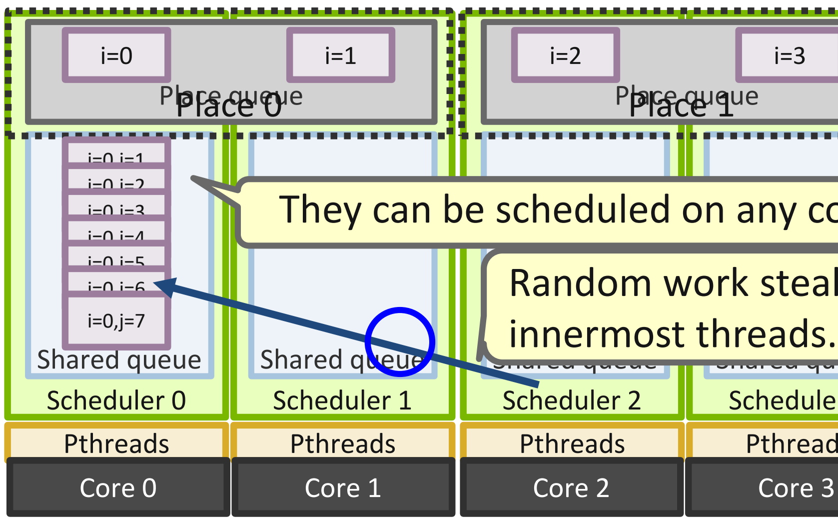
Proposed New PROC_BIND: “unset”

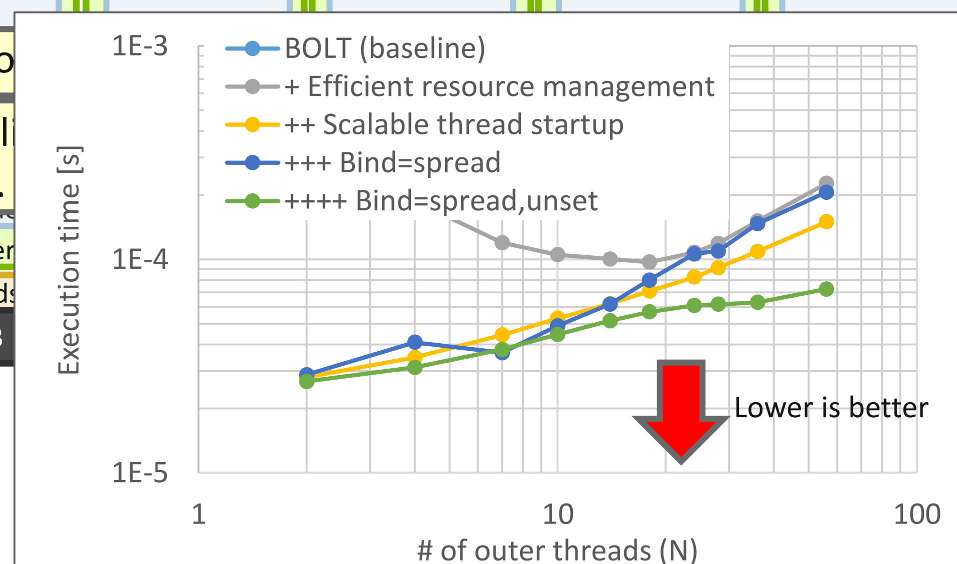
`OMP_WAIT_POLICY=unset`: reset the affinity setting of the specified parallel region.

(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.)

```
// 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);
```

```
// 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);
```





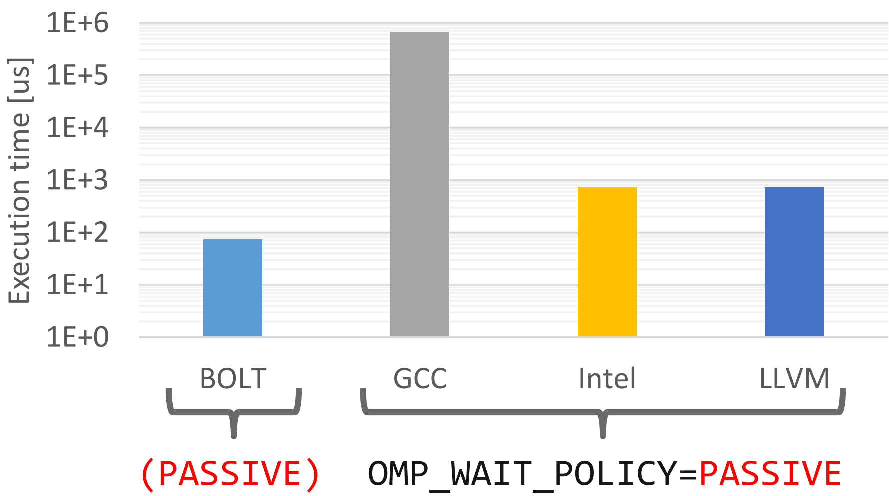
- This scheduling flexibility gives higher performance.

3. Flat Parallelism: Poor Performance

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

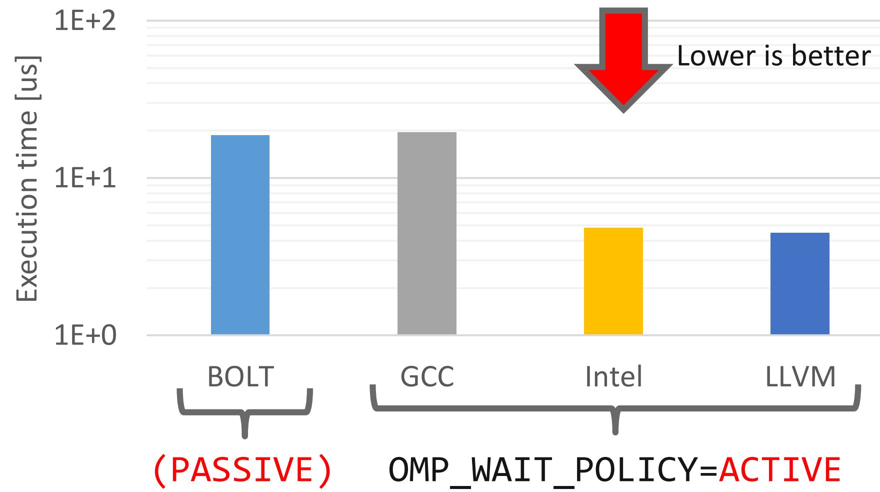
Nested Parallel Regions (no computation)

```
#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.

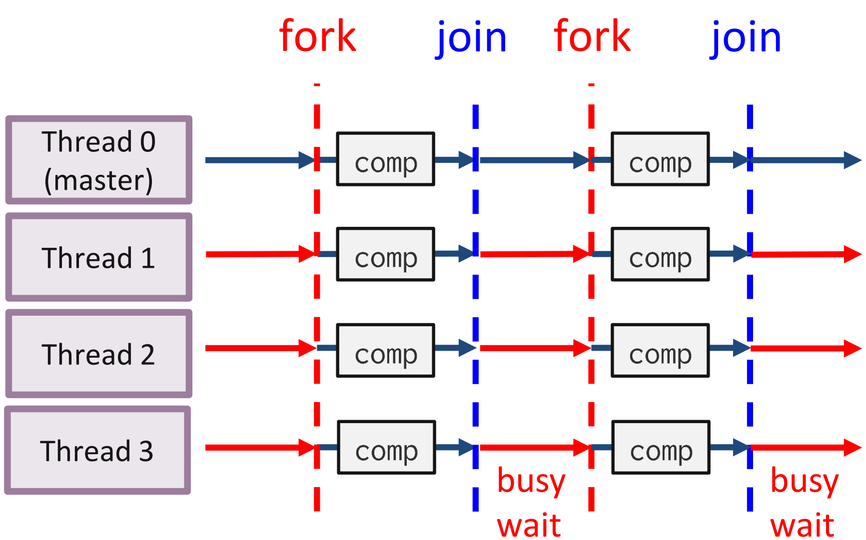
Active Waiting Policy for Flat Parallelism

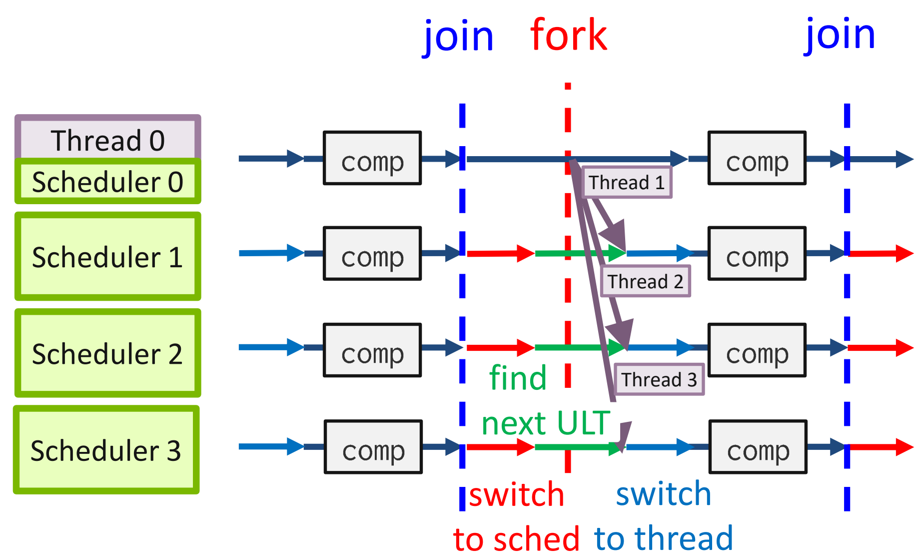
```
for (int iter = 0; iter < n; iter++) {
  #pragma omp parallel for num_threads(4)
  for (int i = 0; i < 4; i++)
    comp(i);
}
```

- 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).





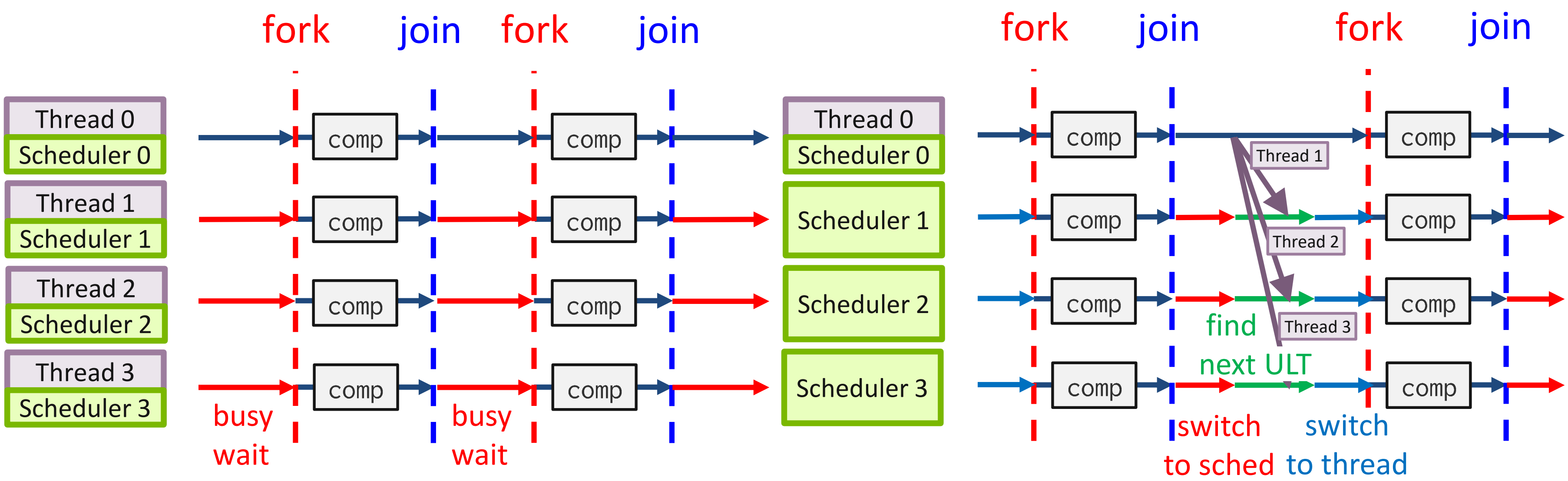
* If passive, after completion of work, threads sleep on a condition variable.

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.

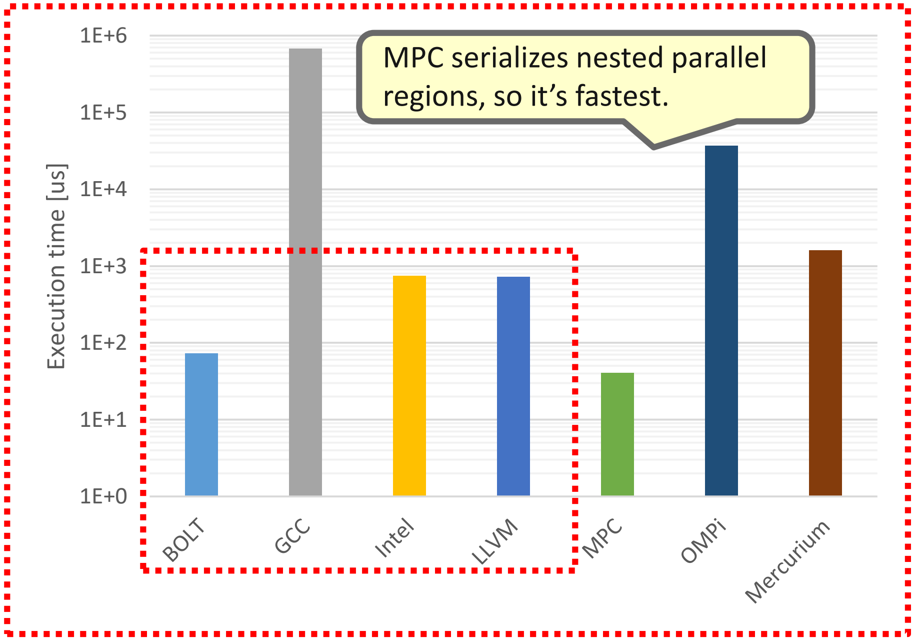


ULT threads are not preemptive, so BOLT periodically yields to a scheduler in order to avoid the deadlock (especially when # of OpenMP threads > # of schedulers).

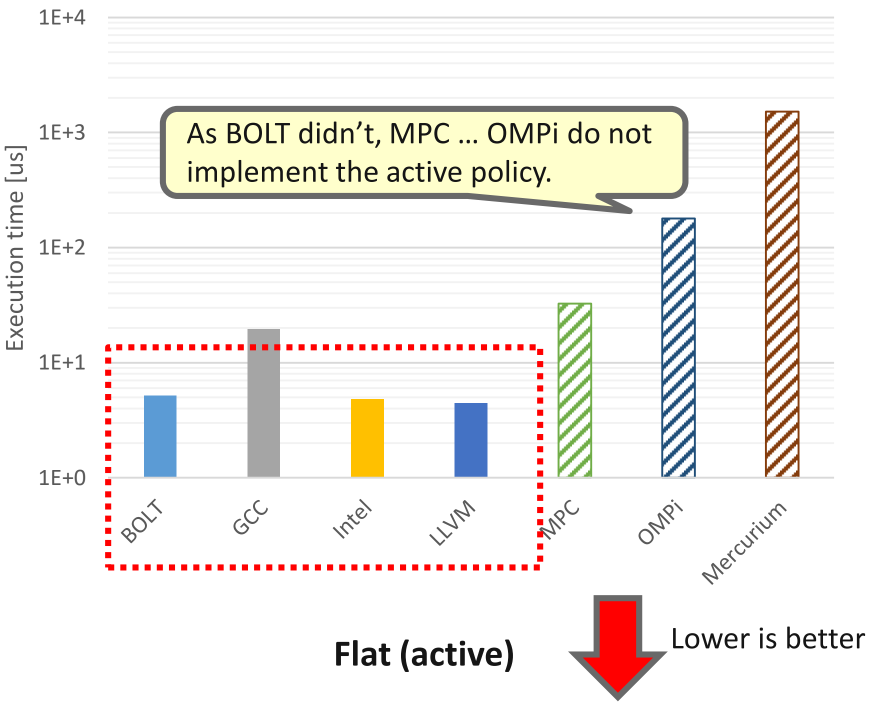
Performance of Flat and Nested

```
#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);
```

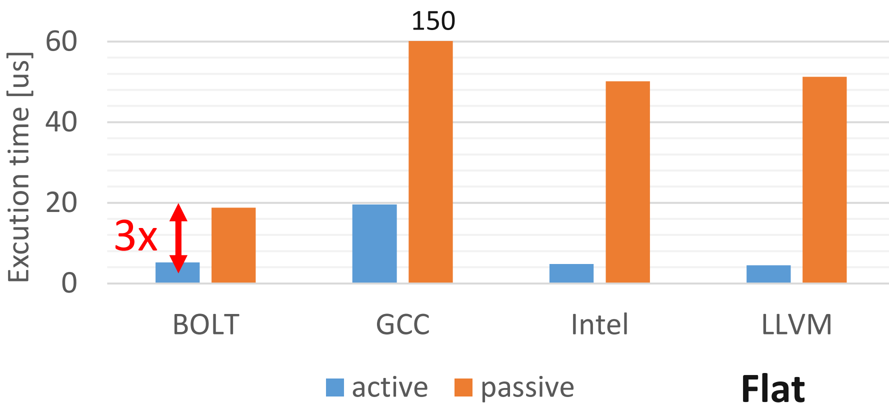


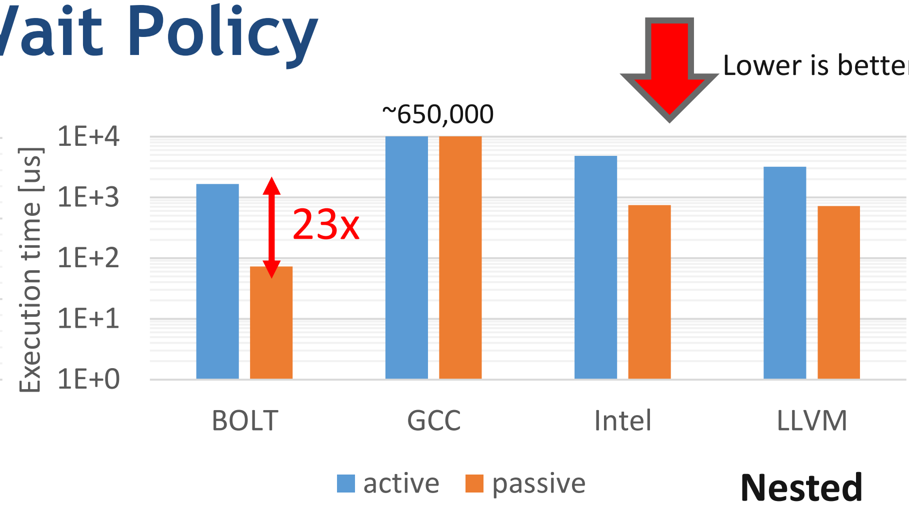
Nested (passive)



Flat (active)

Penalty of the Opposite Wait Policy



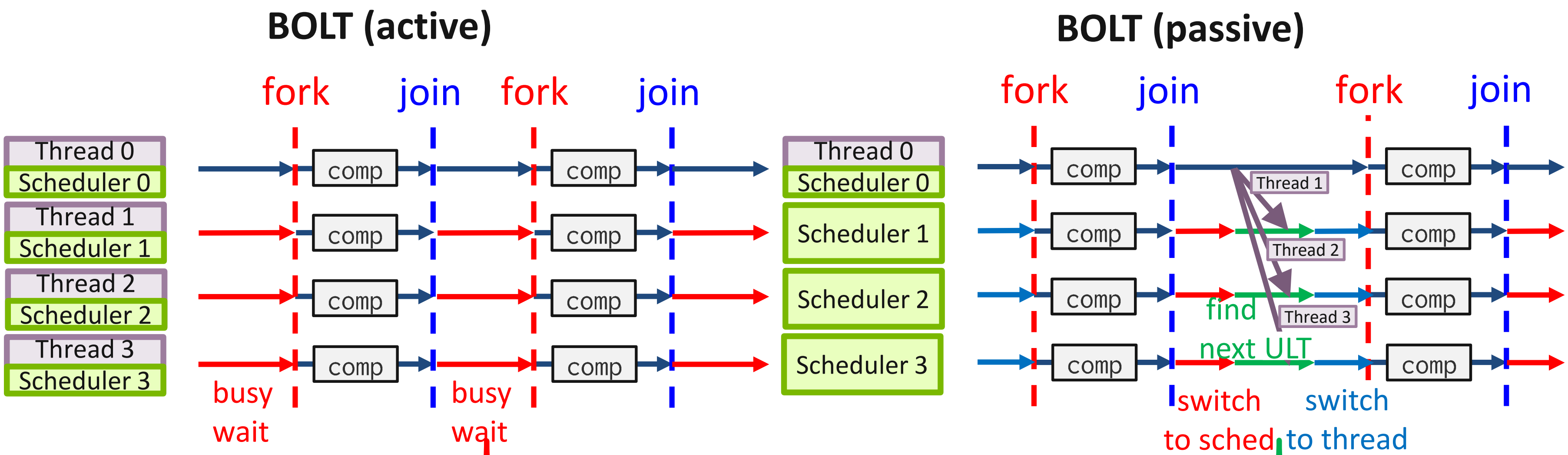



```
#pragma omp parallel for num_threads(56)
for (int i = 0; i < 56; i++)
  #pragma omp parallel for num_threads(56)
  for (int j = 0; j < 56; j++) no_comp(i, j);
```

```
#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

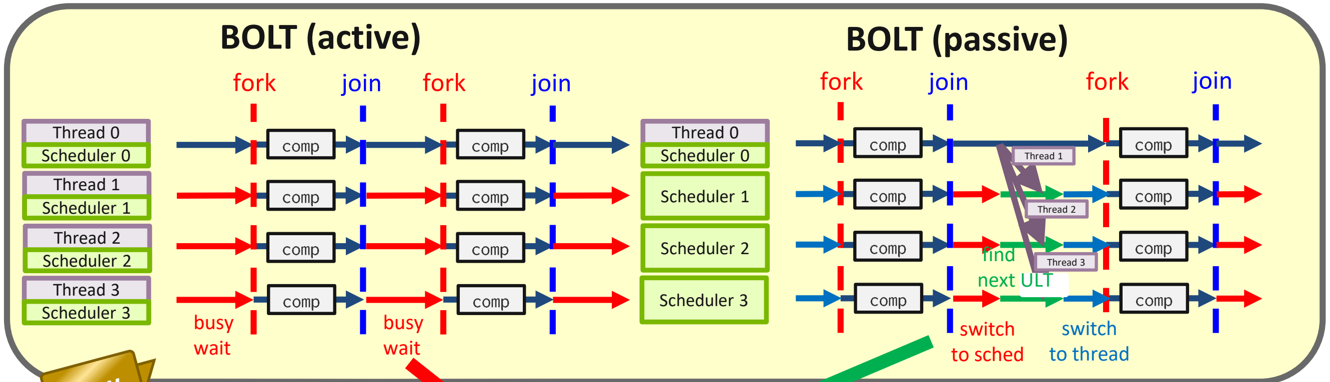


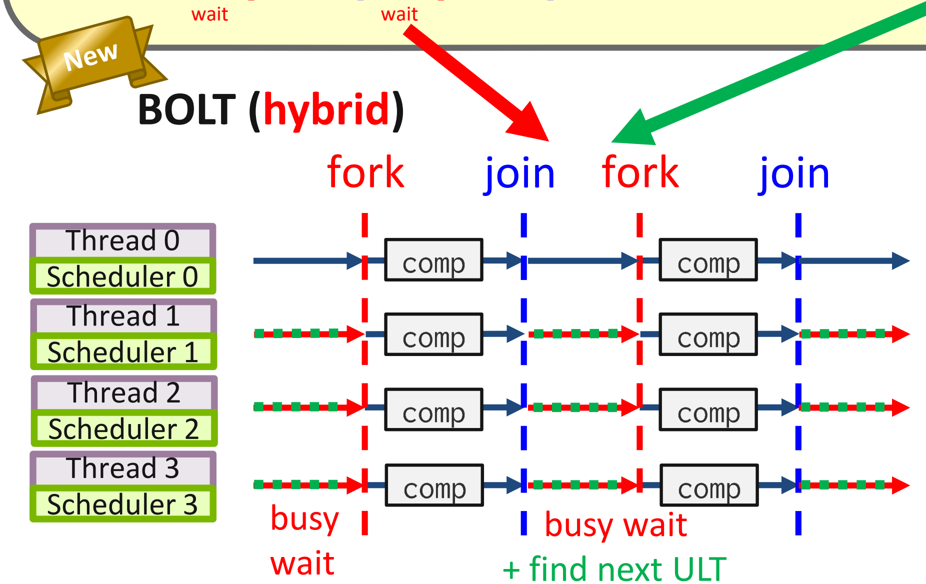

```
void omp_thread() {
RESTART_THREAD:
  comp();
  while (time_elapsed() < KMP_BLOCKTIME) {
    if (team->next_parallel_region_flag)
      goto RESTART_THREAD;
  }
}
```

```
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



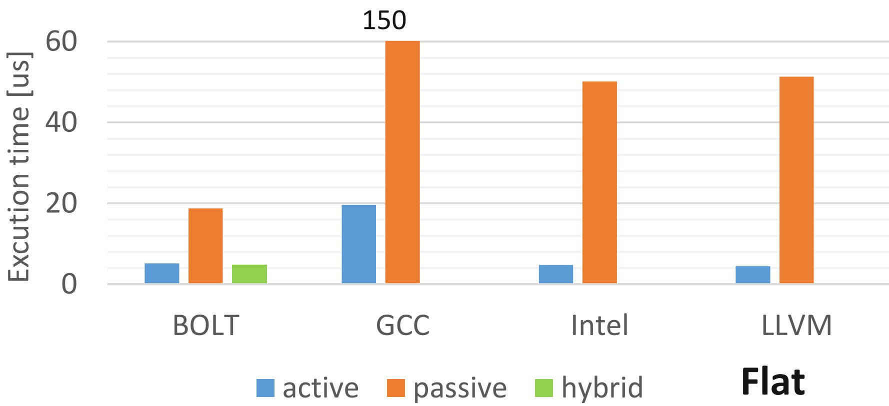



```
void omp_thread() {
RESTART_THREAD:
  comp();
  while (time_elapsed() < KMP_BLOCKTIME) {
    if (team->next_parallel_region_flag)
      goto RESTART_THREAD;
    ULT_t *ult = get_ULT_from_queue
                   (parent_scheduler);
    if (ult != NULL)
      return_to_sched_and_run(ult);
  }
}
```

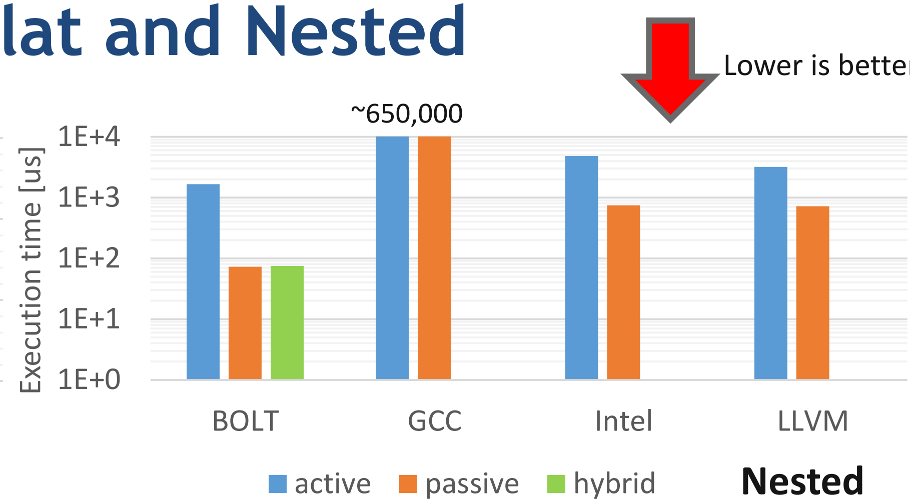
This technique is not applicable to OS-level threads since the scheduler is not revealed.

- 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



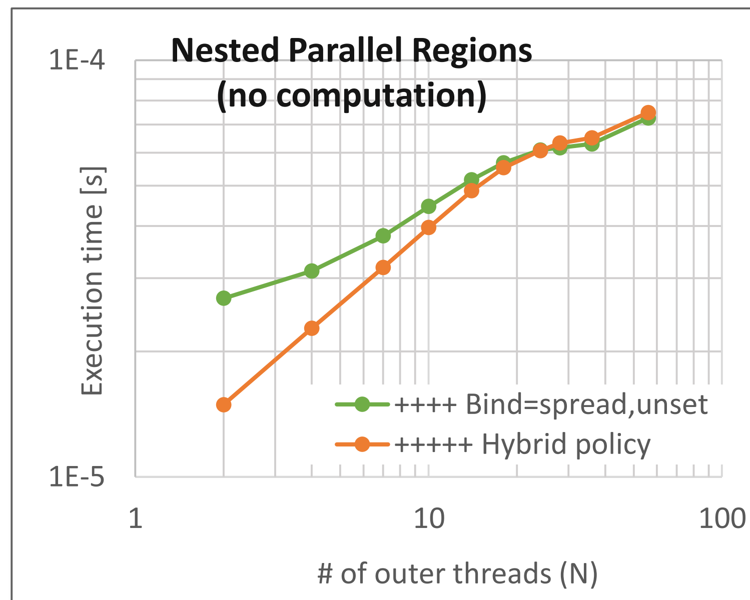
Flat



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);
```

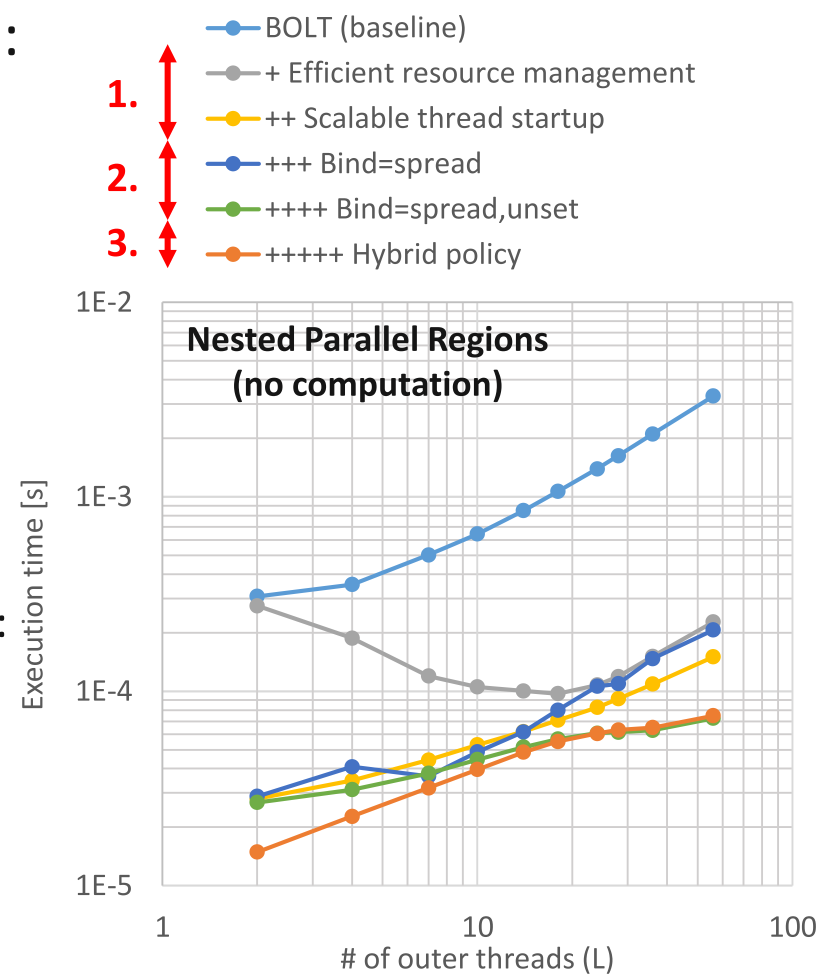


- BOLT (hybrid wait polocy) is always most efficient in both flat and nested cases.
  - We suggest a new keyword “auto” so that the runtime can choose the implementation.

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();
```

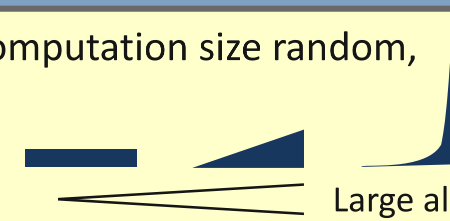


- Our work solely focuses on OpenMP, while some of our techniques are generic:
  - Place queues for affinity of ULTs
  - Hybrid thread coordination for runtimes that have parallel loop abstraction.

Index

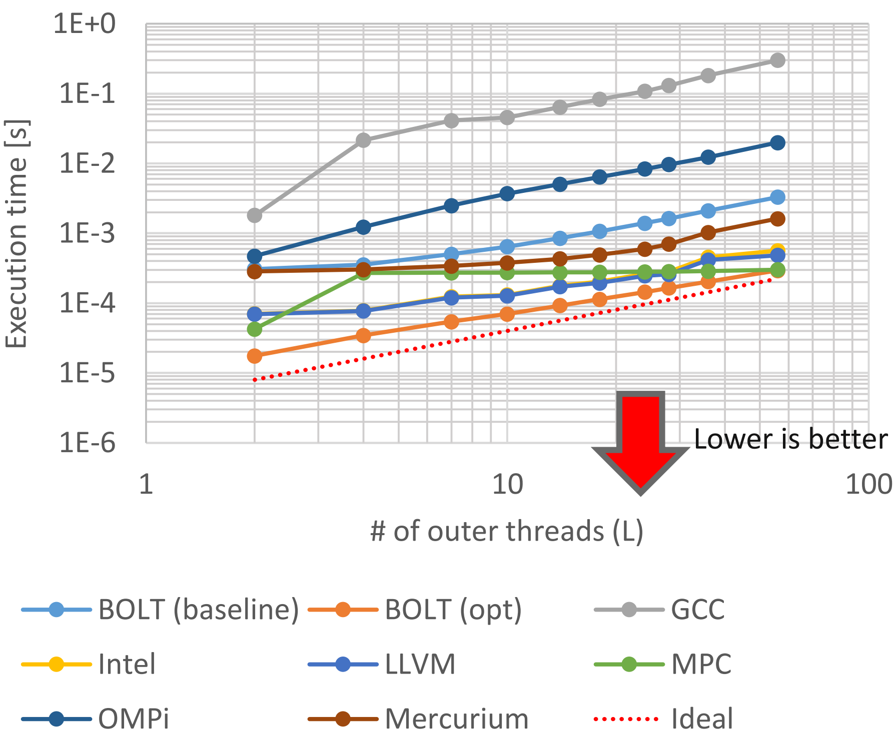
Microbenchmarks

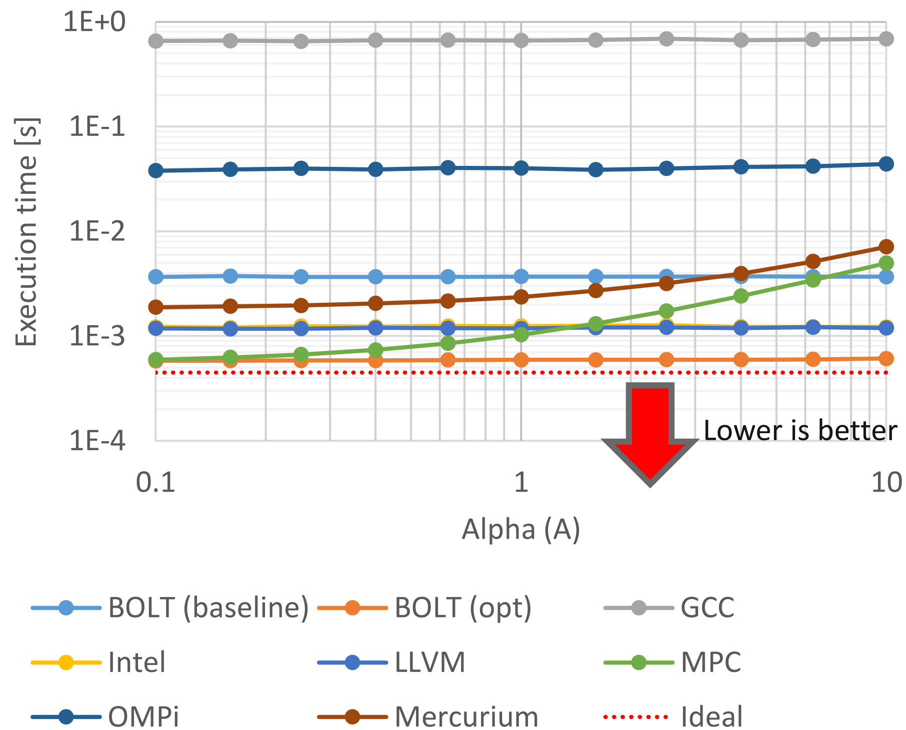
alpha makes the computation size random, while keeping the total problem size.




```
// 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);}
```



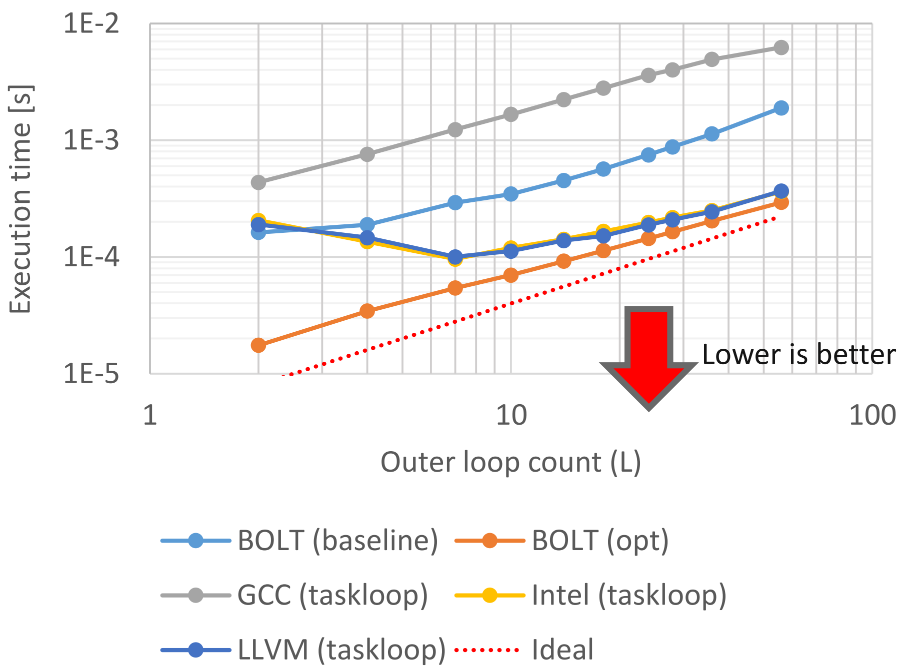


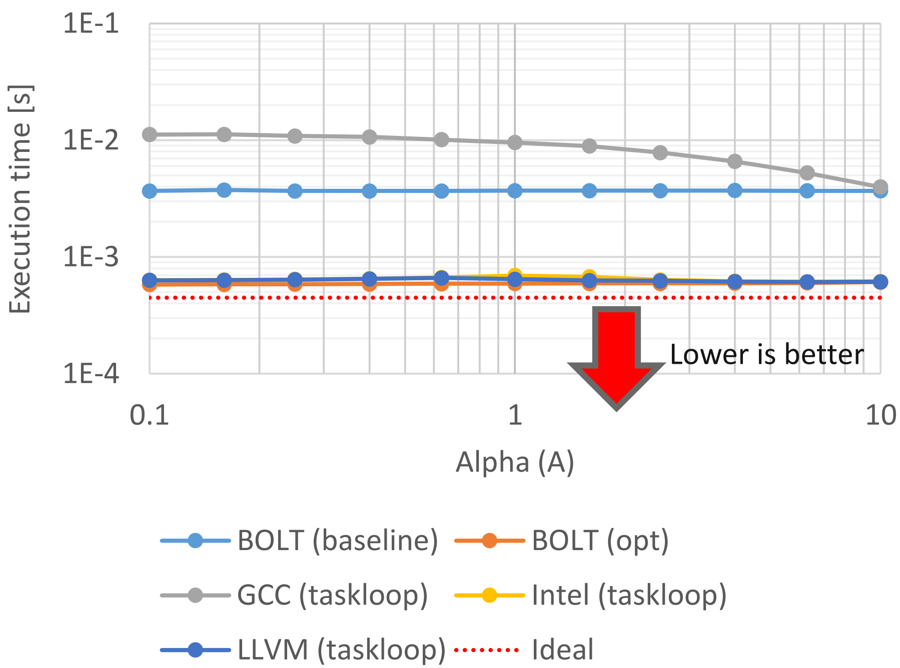
(Ideal): theoretical lower bound under perfect scalability.

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);}
```

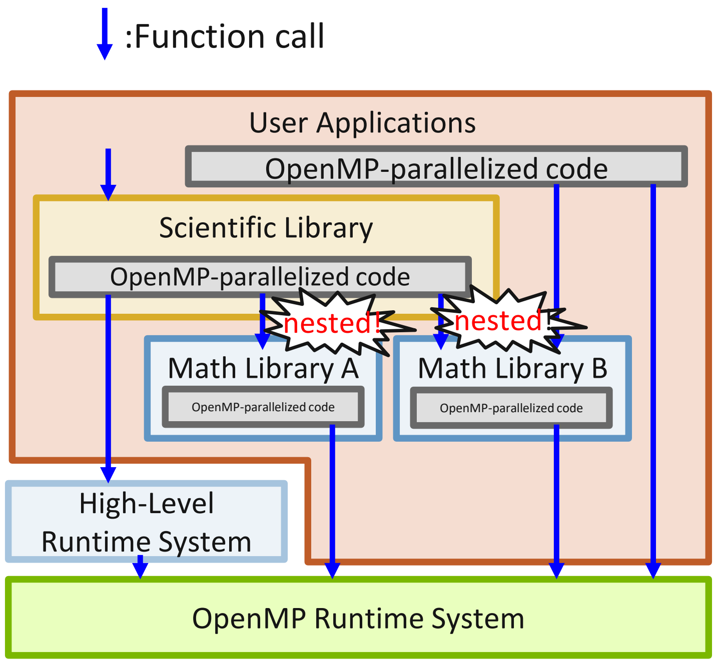




- Parallel regions of BOLT are as fast as taskloop!

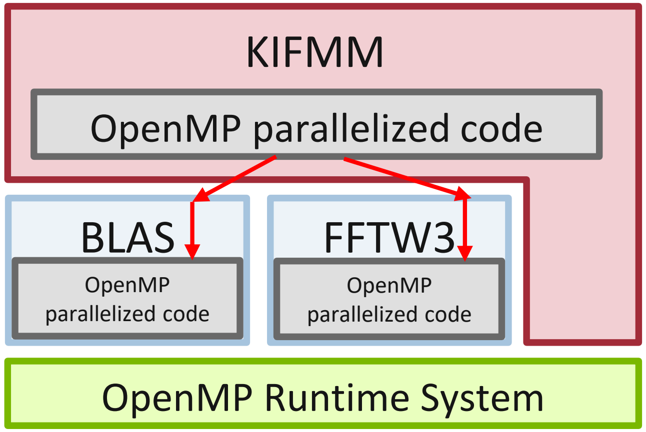
Evaluation: Use Case of Nested Parallel Regions

- The number of threads for outer loops is usually set to # of cores.
  - i.e., if not nested, oversubscription does not happen.
- However, many layers are OpenMP parallelized, which can unintentionally result in nesting.
- We will show two examples.



Evaluation 1: 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.

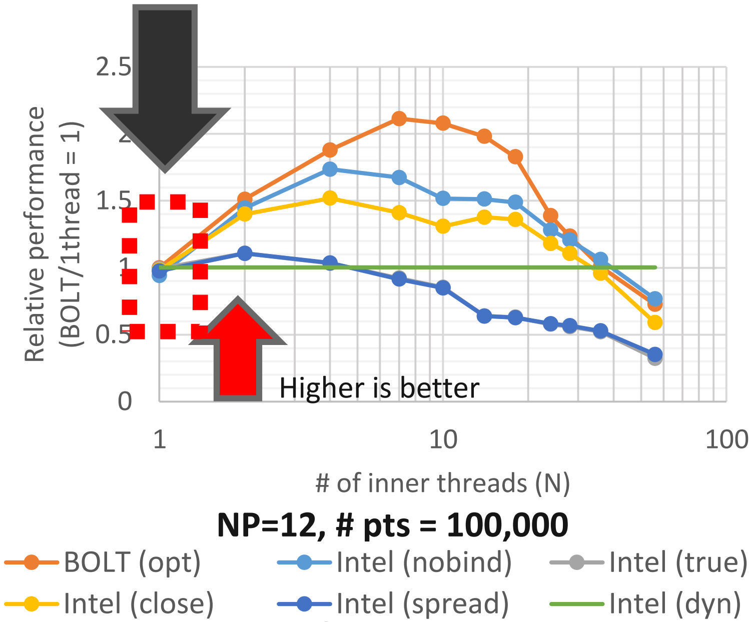



```
for (int i = 0; i < max_levels; i++)
  #pragma omp parallel for
  for (int j = 0; j < nodecounts[i]; j++) {
    [...];
    dgemv(...); // dgemv() creates a parallel region.
  }
```

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

Performance: KIFMM

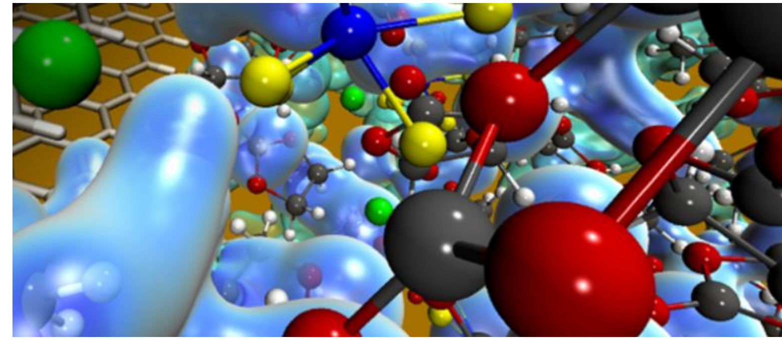
```
void kifmm_upward():
  for (int i = 0; i < max_levels; i++)
    #pragma omp parallel for num_threads(56)
    for (int j = 0; j < nodecounts[i]; j++) {
      [...];
      dgemv(...); // creates a parallel region.
    }

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



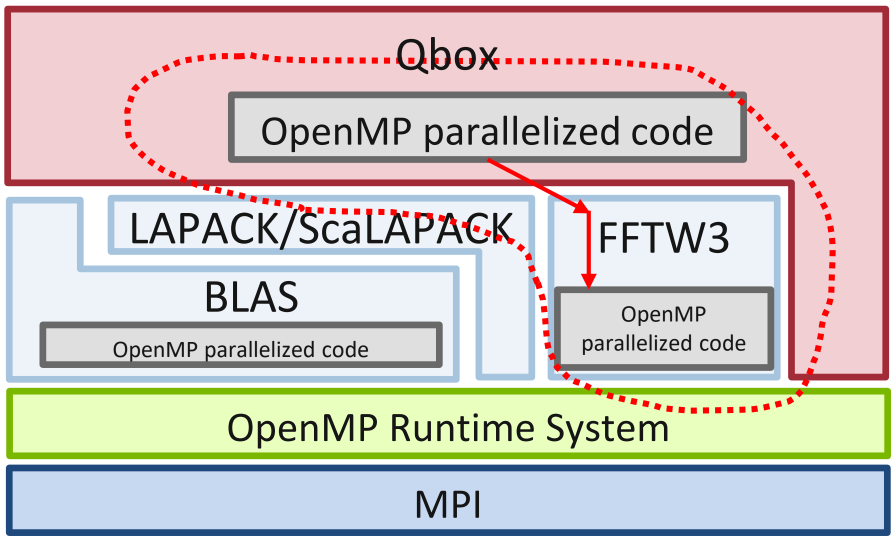
Different Intel OpenMP configurations:
nobind(=false),true,close,spread: proc_bind
dyn: MKL_DYNAMIC=true
Note that other parameters are hand tuned (see the paper).

- 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.

Evaluation 2: FFT in QBox

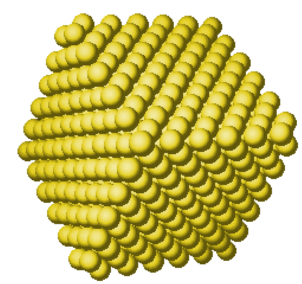


- Qbox[*]: first-principles molecular dynamics code.
- We focus on the FFT computation part.




```
// FFT backward
#pragma omp parallel for
for (int i = 0; i < num / nprocs; i++)
  fftw_execute(plan_2d, ...);

void fftw_execute(...): // in FFTW3
  [...];
  #pragma omp parallel for num_threads(N)
  for (int i = 0; i < [...]; i++)
     fftw_sequential(...);
```

- We extracted this FFT kernel and change the parameters based on the gold benchmark.

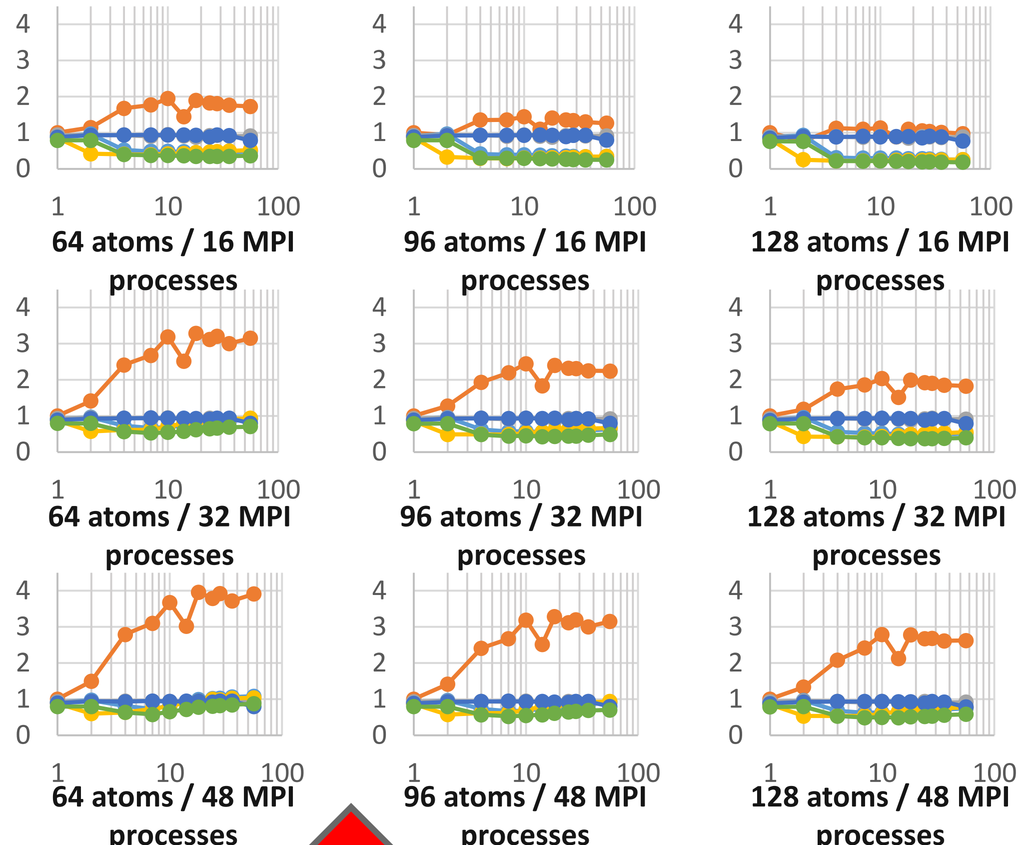


[*] F. Gygi, "Architecture of Qbox: A scalable first-principles molecular dynamics code," IBM Journal of Research and Development, vol. 52, no. 1.2, pp. 137–144, Jan. 2008.

Performance: FFTW3

X axis: # of inner threads (N)
Y axis: relative performance (BOLT + N=1: 1.0)

```
// FFT backward
#pragma omp parallel for
for (int i = 0; i < num / nprocs; i++)
  fftw_execute(plan_2d, ...);

void fftw_execute(...): // in FFTW3
  [...];
  #pragma omp parallel for num_threads(N)
  for (int i = 0; i < [...]; i++)
     fftw_sequential(...);
```



BOLT (opt) Intel (nobind) Intel (true)
Intel (close) Intel (spread) Intel (dyn)

Intel OpenMP configurations: nobind(=false),true,close,spread: proc_bind, dyn: OMP_DYNAMIC=true

- nprocs = # of MPI nodes
- num (and fftw size) is proportional to # of atoms.

Higher is better

Experiments on KNL 7230 64 cores.
 # of threads for the outer parallel region = 64
 # of threads for the inner parallel region = N (changed)

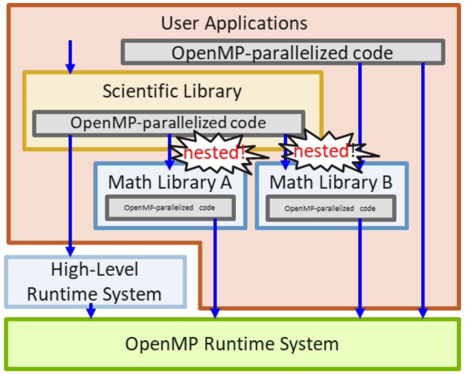
More beneficial for nested parallel regions.
=> Strong scaling

- N=1 (flat): performance is almost the same.
- N>1 (nested): BOLT further increased performance.

Index

1. Introduction
2. Existing Approaches
   - OS-level thread-based approach
   - User-level thread-based approach
     - What is a user-level thread (ULT)?
3. BOLT for both Nested and Flat Parallelism
   - Scalability optimizations
   - ULT-aware affinity (proc_bind)
   - Thread coordination (wait_policy)
4. Evaluation
5. **Conclusion**

Summary of this Talk

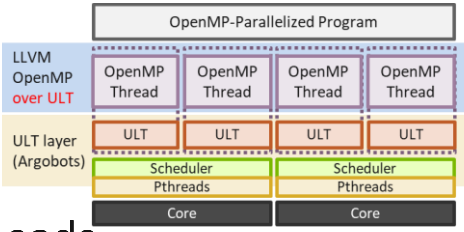


- Nested OpenMP parallel regions are commonly seen in complicated software stacks.
  => Demand for efficient OpenMP runtimes
  to exploit both flat and nested parallelism.
- BOLT: an lightweight OpenMP library over ULT.
  - Simply using ULTs is insufficient:
    - Solve scalability bottlenecks in the 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.

Thank you for listening!

- BOLT: http://www.bolt-omp.org
- Q&A (as a software):
  - What is the goal of the BOLT project?
    - Improve OpenMP by ULTs:
      - 1. enrich OpenMP tasking features with least overheads,
      - 2. minimizing overheads of OpenMP threads, and 3. more.
  - How to use it?
    - BOLT is a runtime library: no special compiler is required.
      GCC/ICC/Clang + LD_LIBRARY_PATH+=${BOLT_INSTALL_PATH} works.
  - Is BOLT stable?
    - Regularly checked with LLVM OpenMP tests (GCC 8.x, ICC 19.x, and Clang 10.x)
  - What OpenMP features are supported?
    - OpenMP 4.5 including task,
      task depend, and offloading.

Artifact:
https://zenodo.org/record/3372716
(DOI: 10.5281/zenodo.3372716)



Much engineering efforts for ABI compatibility and stability.

Future work:
- Enhance task scheduling
- MPI+OpenMP interoperability

Acknowledgment

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BOLT is part of the ECP SOLLVE project: https://www.bnl.gov/compsci/projects/SOLLVE/