Comparison and analysis of parallel tasking performance for an irregular application

Patrick Atkinson, University of Bristol (p.atkinson@bristol.ac.uk)

Simon McIntosh-Smith, University of Bristol

University of BRISTOL

Intel® HPC Developer Conference 2017

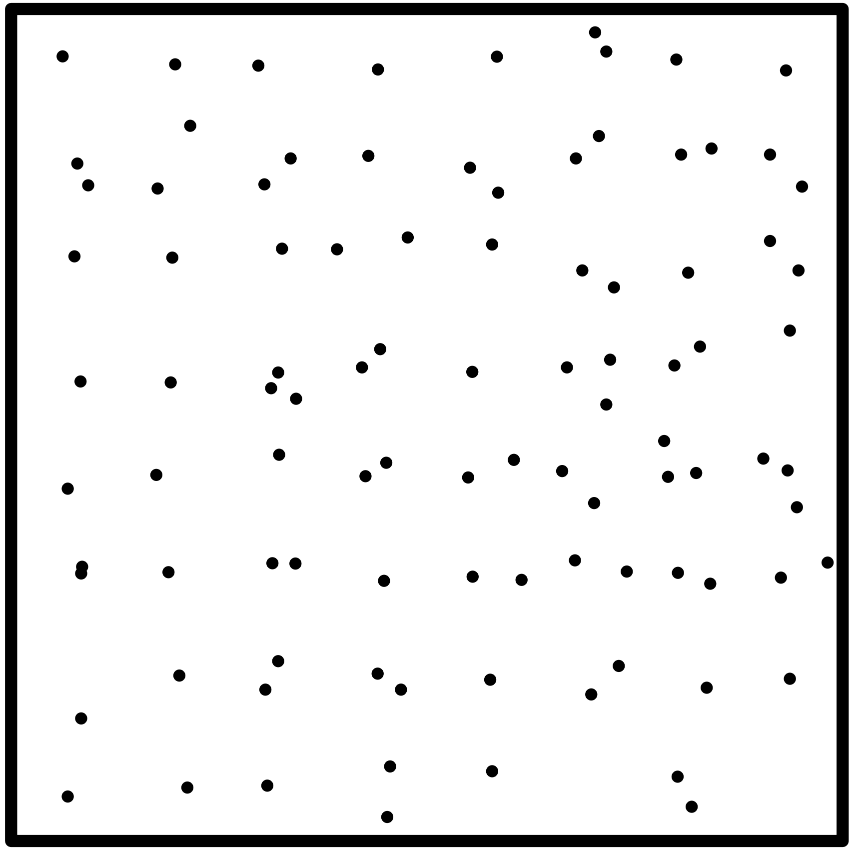
Motivation

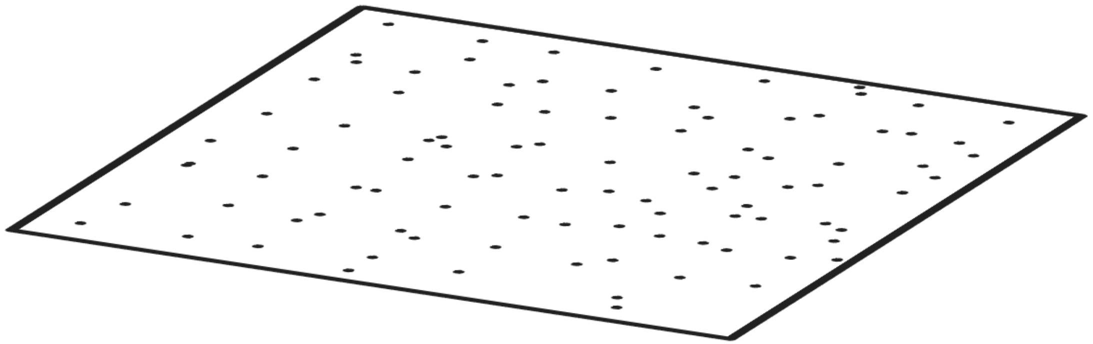
- Exploring task parallelism through a new mini-app (https://github.com/UoB-HPC/minifmm)
- Discovering limitations in OpenMP tasking model
- Optimising OpenMP implementation of algorithm through alternatives to task constructs
- Comparing performance of tasking in OpenMP runtime implementations and to other parallel frameworks
- Determining whether using tasks can perform as well as data-parallel implementations whilst reducing code-size

Fast Multipole Method overview

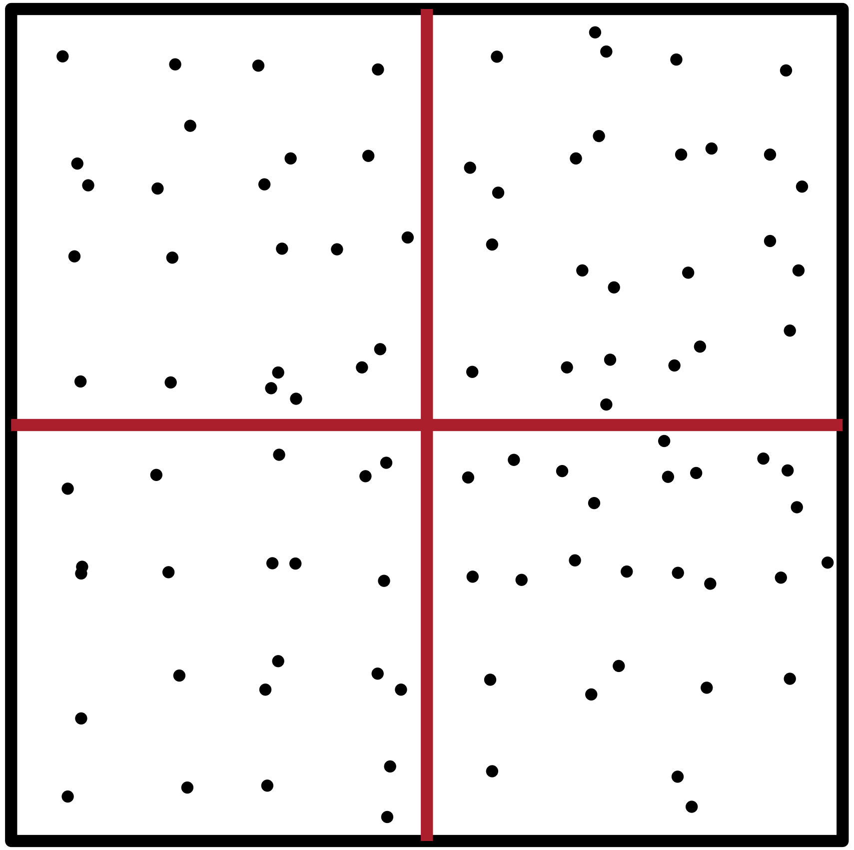
- Used for solving N-body problems
- Reduces time complexity from $O(n^2)$ to $O(n)$
- Compute bound method
- Good fit for tasking for for tasking due to complex control flow – dependant on particle data
- Applications include: astrophysics, electrostatics, fluid dynamics, electromagnetics

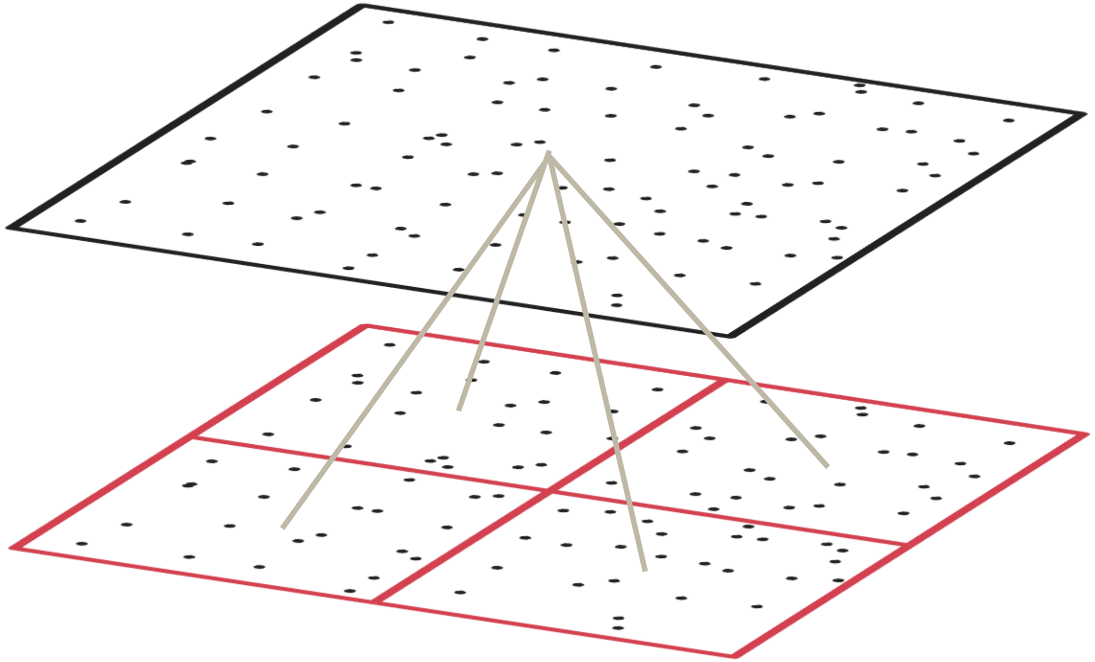
FMM domain decomposition



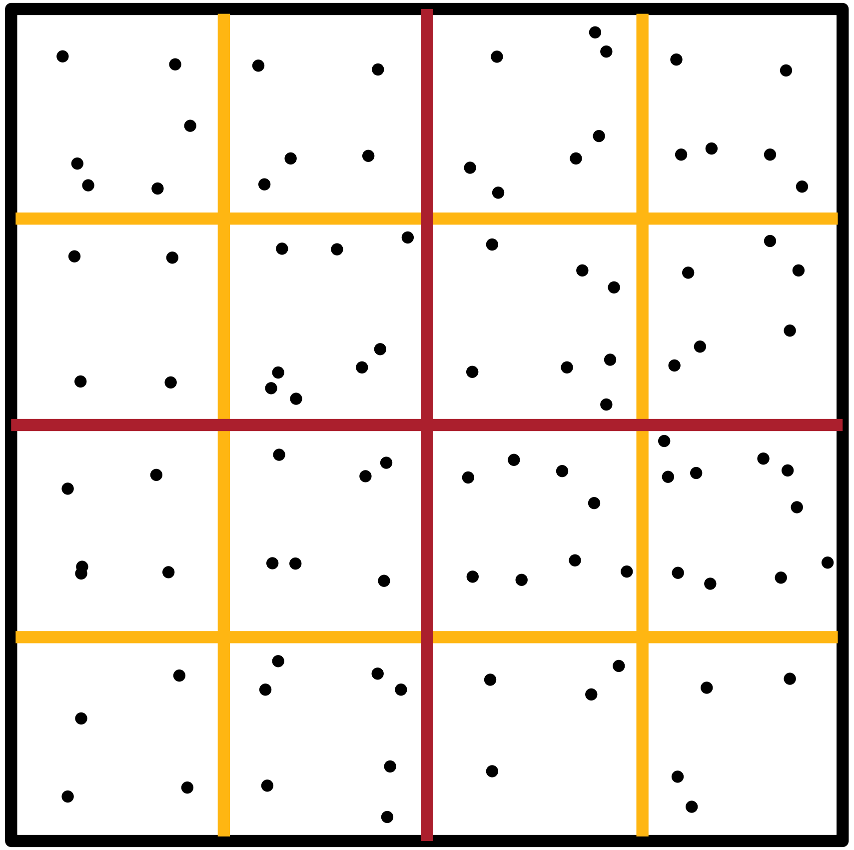


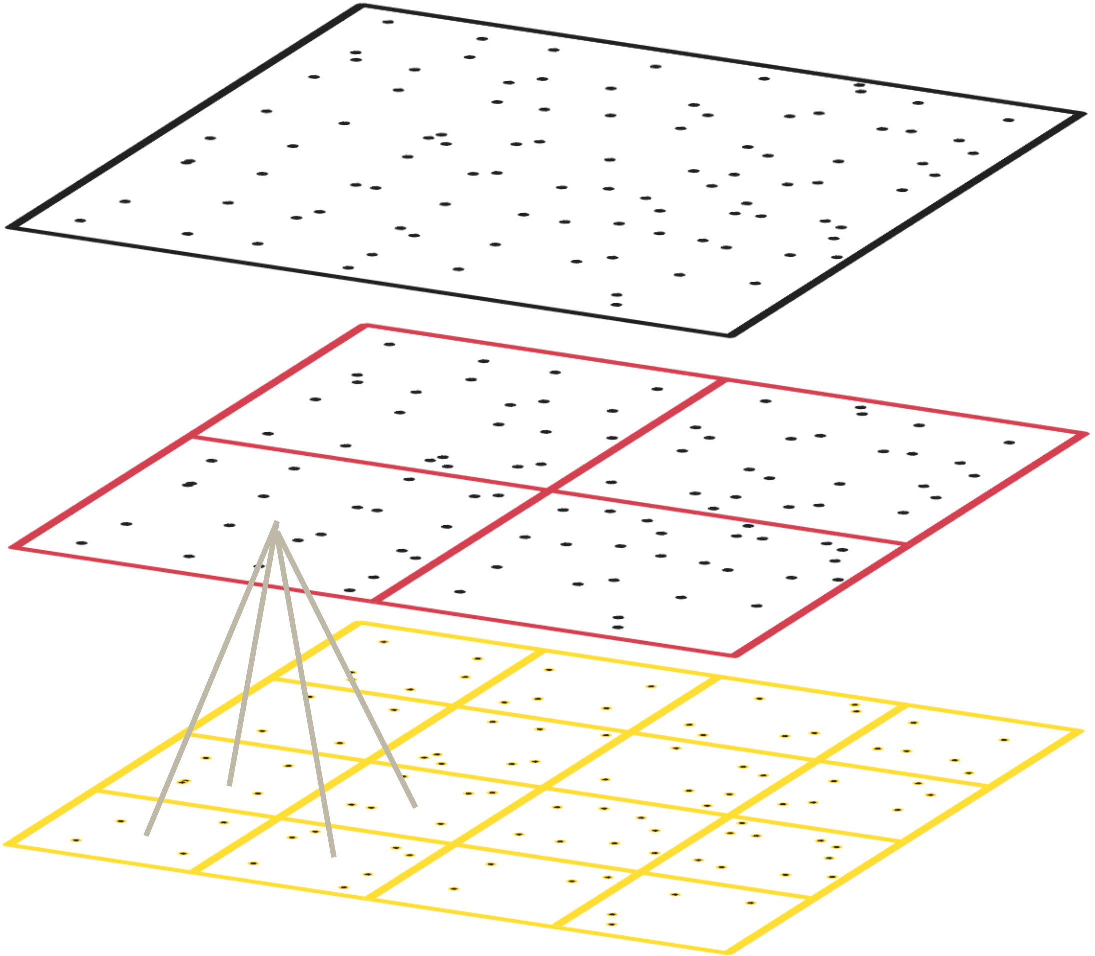
FMM domain decomposition



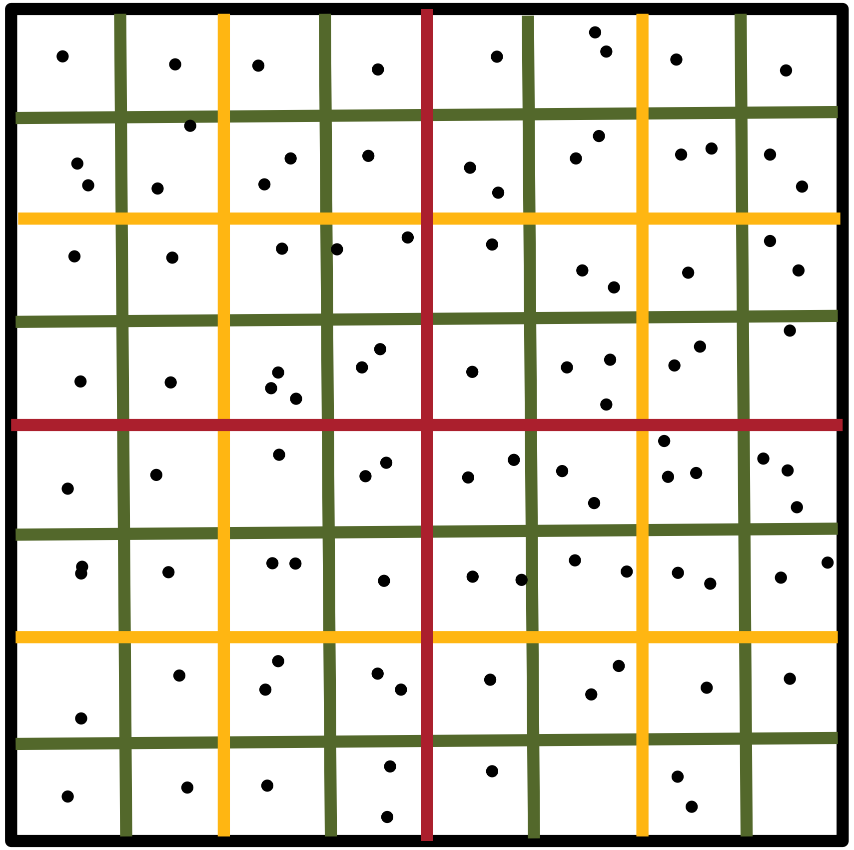


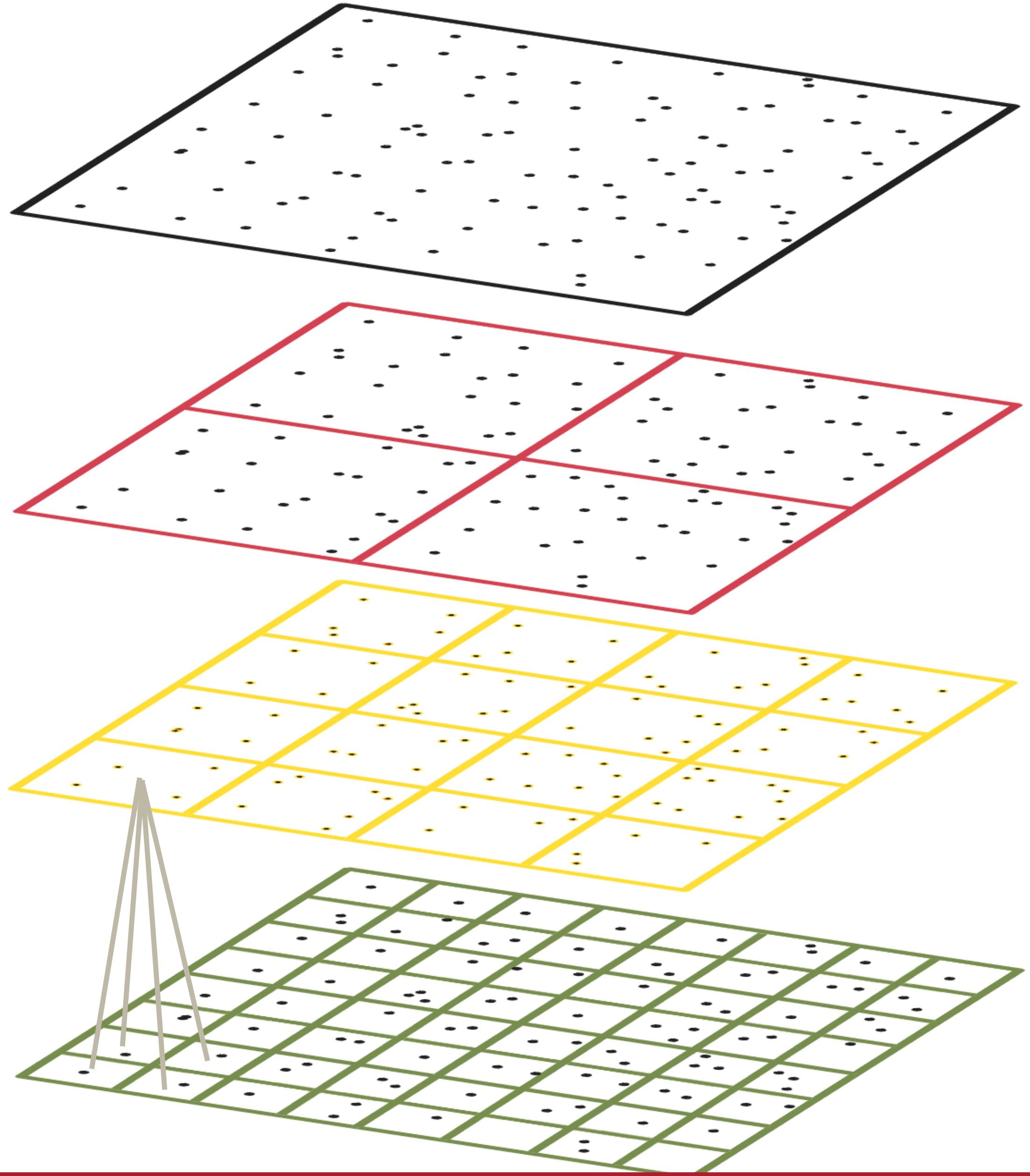
FMM domain decomposition





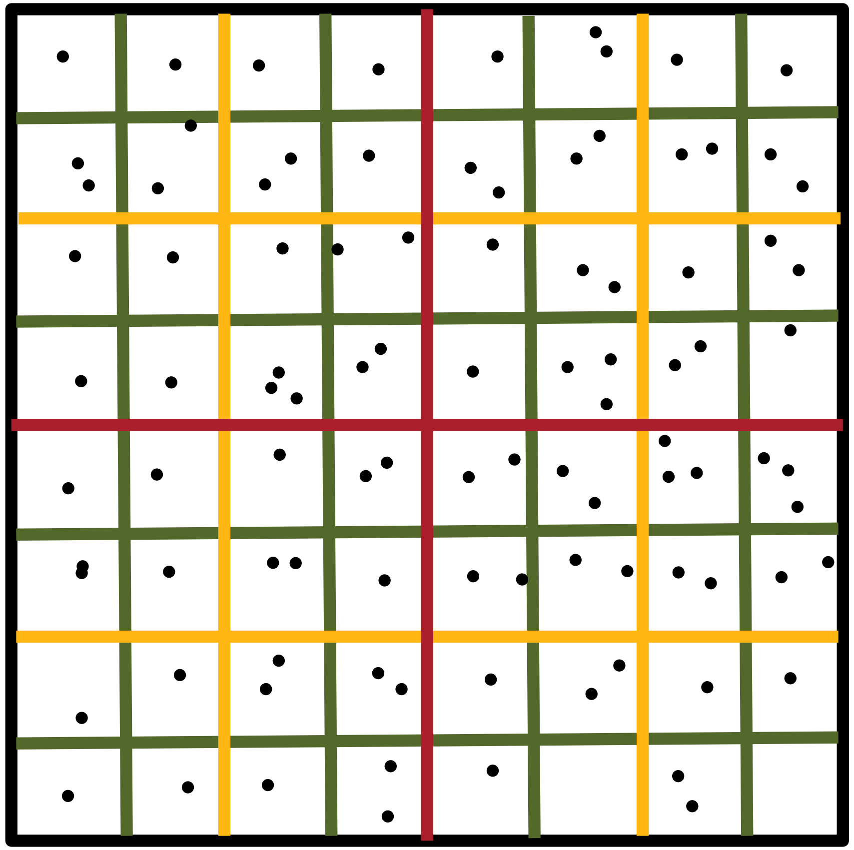
FMM domain decomposition





Method

- Each node in the tree will perform interactions with many other nodes
- Interaction type determined by distance between nodes and user-defined parameter
- Recurse until either:
  - If two nodes are well-separated the interaction is approximated (node to node interaction)
  - The leaf level is reached and the particle interaction is calculated directly (particle to particle interaction)

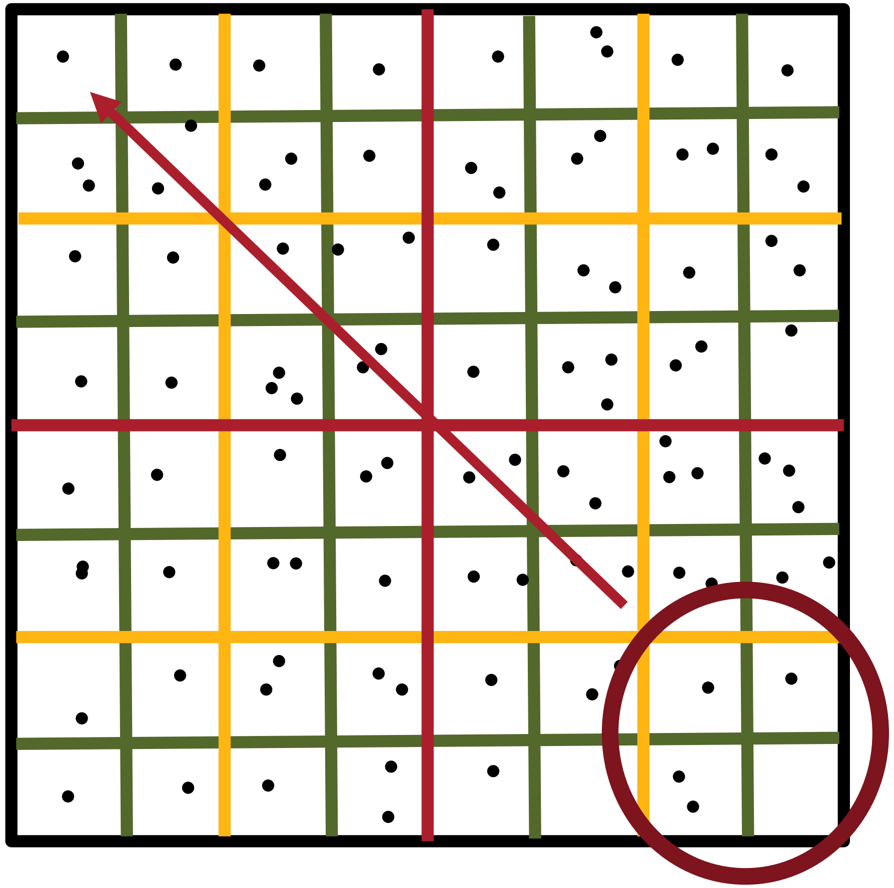


Method

- Each node in the tree will perform interactions with many other nodes

- Interaction type determined by distance between nodes and user-defined parameter

- Recurse until either:
  - **If two nodes are well-separated the interaction is approximated (node to node)**
  - The leaf level is reached and the particle interaction is calculated directly (particle to particle)

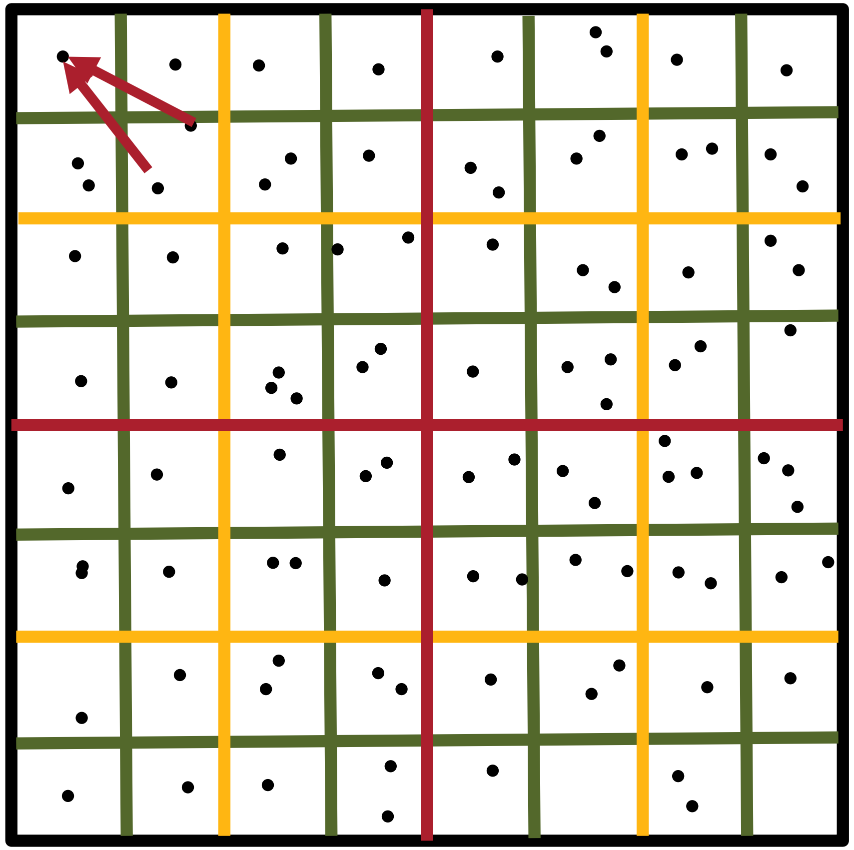


Method

- Each node in the tree will perform interactions with many other nodes

- Interaction type determined by distance between nodes and user-defined parameter

- Recurse until either:
  - If two nodes are well-separated the interaction is approximated (node to node)
  - **The leaf level is reached and the particle interaction is calculated directly (particle to particle)**



Using tasks for FMM

- We have many interactions to perform between groups of particles
- Interaction type dependant on distance between tree nodes – not known until runtime
- Tree could be highly imbalanced

Using tasks for FMM

- We have many interactions to perform between groups of particles
- Interaction type dependant on distance between tree nodes – not known until runtime
- Tree could be highly imbalanced

Solution? Use tasks

```
#pragma omp task
calculate_force(target, source)
```

- Create task for each interaction
- Letting some thread complete the required work at any time
- Need a way to enforce two threads don't update same values…

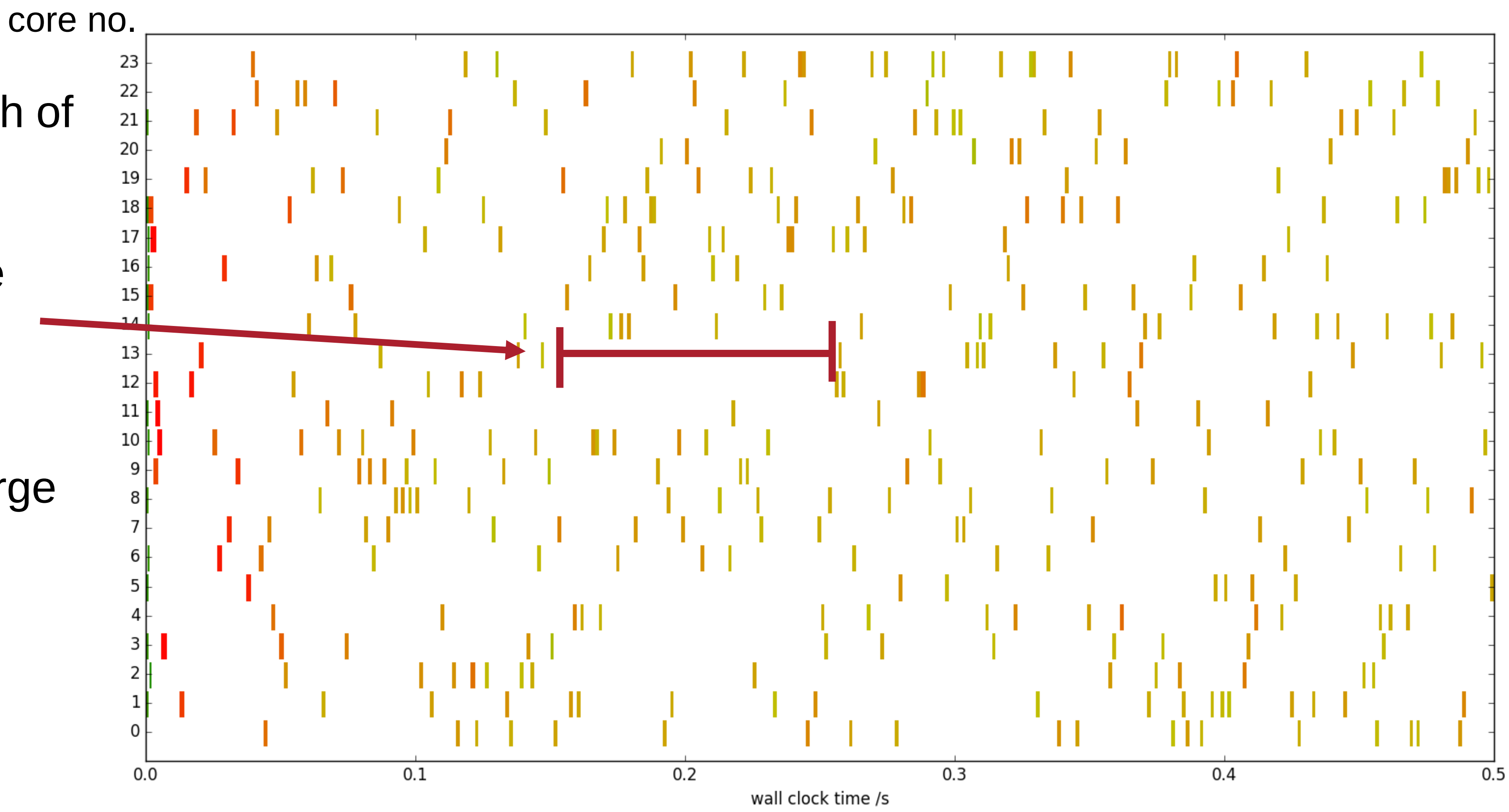
Intuitive implementation with task dependencies

```
function DTT(target, source)
    // calculate distance between target and source
    ...
    if source and target well seperated then
        #pragma omp task depend(inout: target)
        ApproximateForce(target, source)
    else if target and source are leaves then
        #pragma omp task depend(inout: target)
        DirectForce(target, source)
    else
        if target.radius > source.radius then
            for each child in target do
                DTT(child, source)
        else
            for each child in source do
                DTT(target, child)
```

- Generate task for each interaction type
- Nodes/cells typically contain O(100) particles - enough work to for single task
- Allows for fine-grained synchronisation with other stages of algorithm using task dependencies
- The order tasks are generated in determines order of execution

Effect of enforcing unnecessary ordering

- Plotting execution of each of the calculation functions
- Whitespace = thread idle time
- Unnecessary ordering of dependencies causes large amounts of idle time



Performance gain from removing dependencies

```
function DTT(target, source)
    ...
    if source and target well seperated then
        #pragma omp task ~~depend(inout: target)~~
        ApproximateForce(target, source)
    else if target and source are leaves then
        #pragma omp task ~~depend(inout: target)~~
        DirectForce(target, source)
    else
        // recurse
        ...
```

- Investigation – what happens if we remove dependencies?
- Incorrect behaviour due to multiple threads updating same nodes
- However, much better thread utilisation…

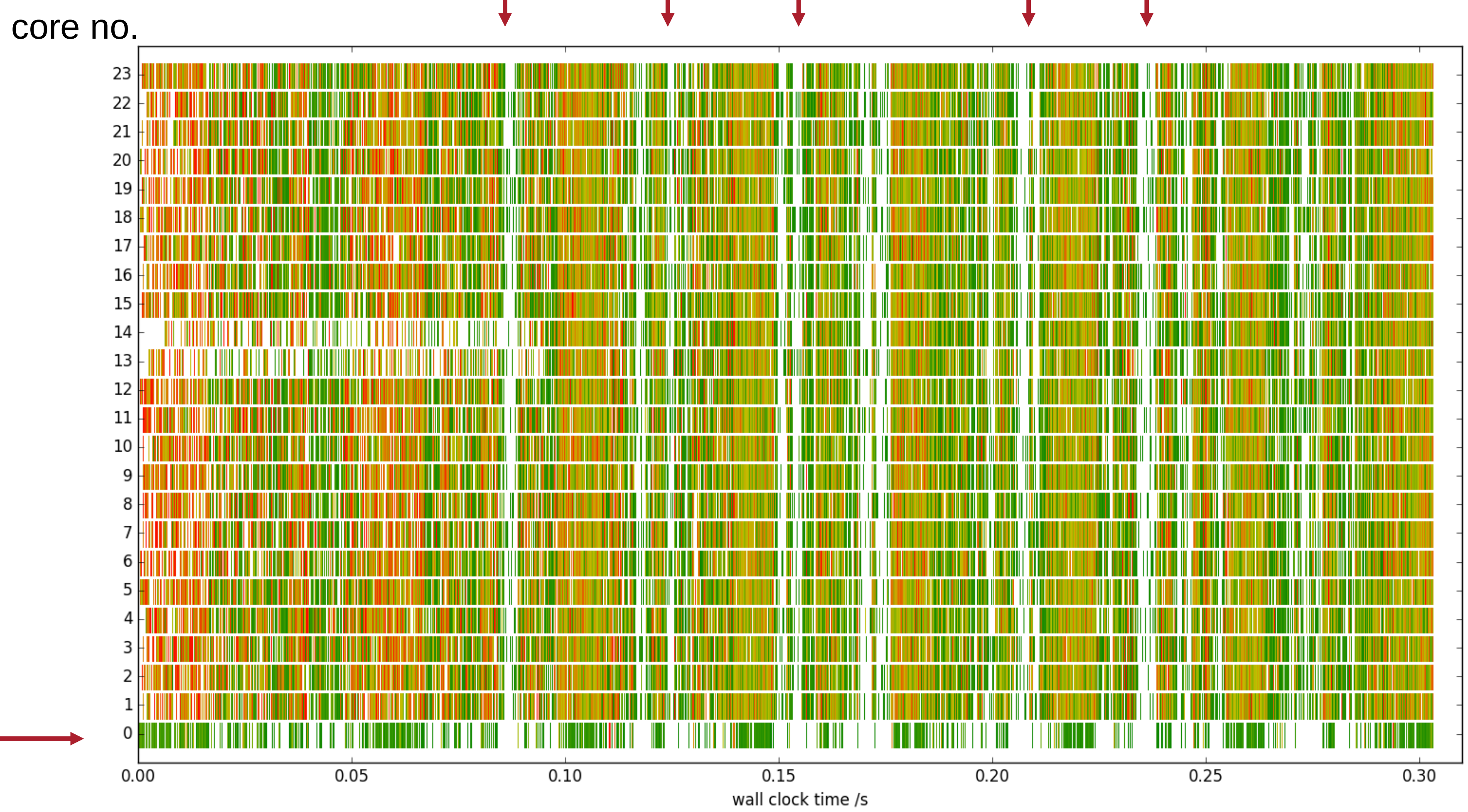
Effect of a single thread generating tasks – 24 core Ivybridge

Significantly less idle time than before, however…

Effect of a single thread generating tasks – 24 core Ivybridge

Threads lacking tasks to execute

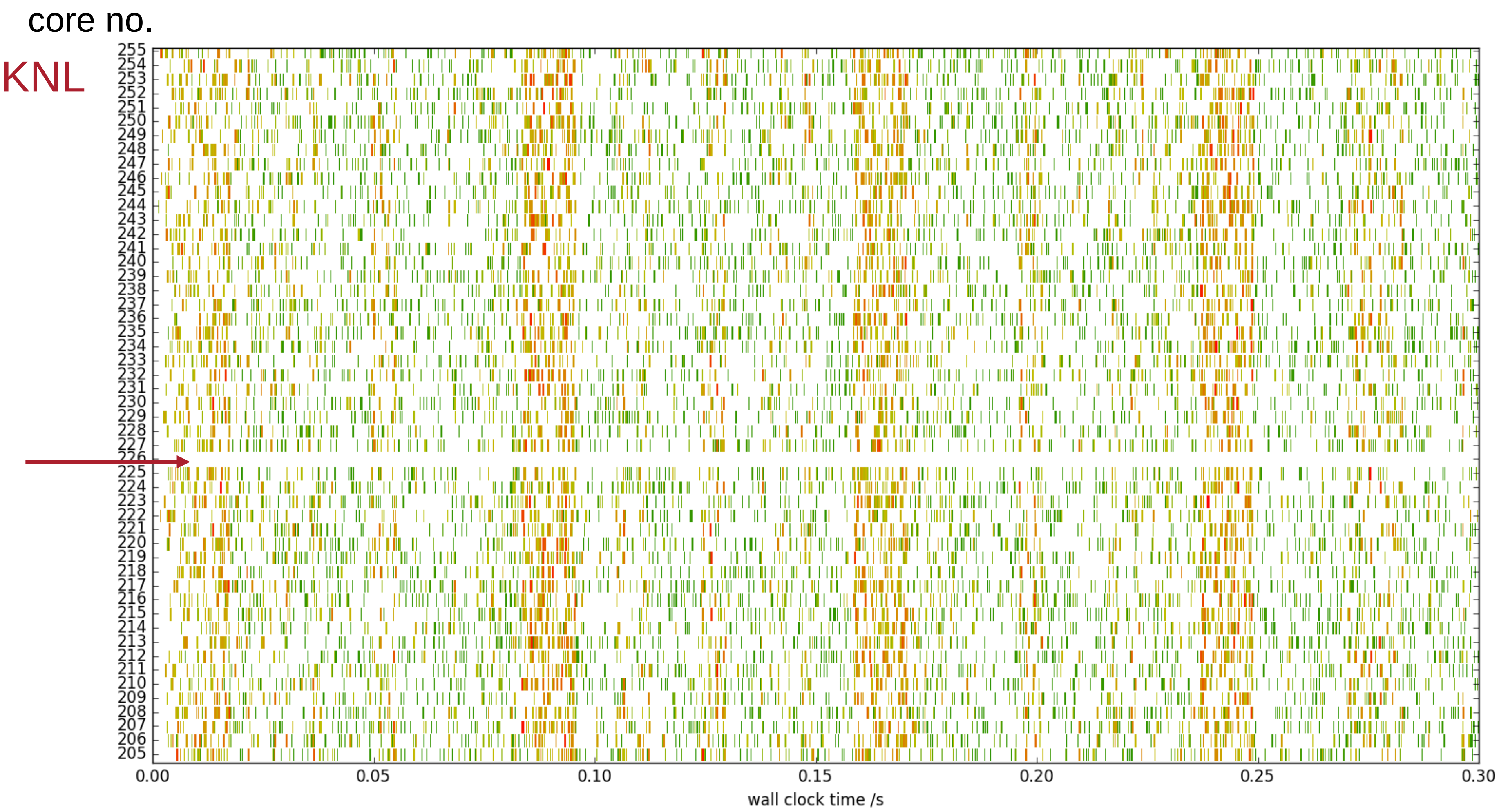
Thread generating tasks



Effect of a single thread generating tasks – 256 threads, KNL

Problem even worse for KNL

Thread generating tasks



Threads 0 – 204 not shown

So two issues…

- Need an efficient way to handle race condition
  -> Ensure mutual exclusion through locks or atomics

- Can't generate all tasks from single thread
  -> Need to perform tree traversal in parallel

Locking nodes of tree

- Lock target node while updating values
- `taskyield` – allows programmer to specify task can be suspended
- Combine `taskyield` with locks so thread encountering task can switch to another task
- `untied task` – task can be resumed by any thread
- Can combine both `taskyield` and `untied` with locks

```
void force_calculation(node target, node source)
{
    omp_set_lock(&target->lock);

    // caculate or approximate force
    ...

    omp_unset_lock(&target->lock);
}
```

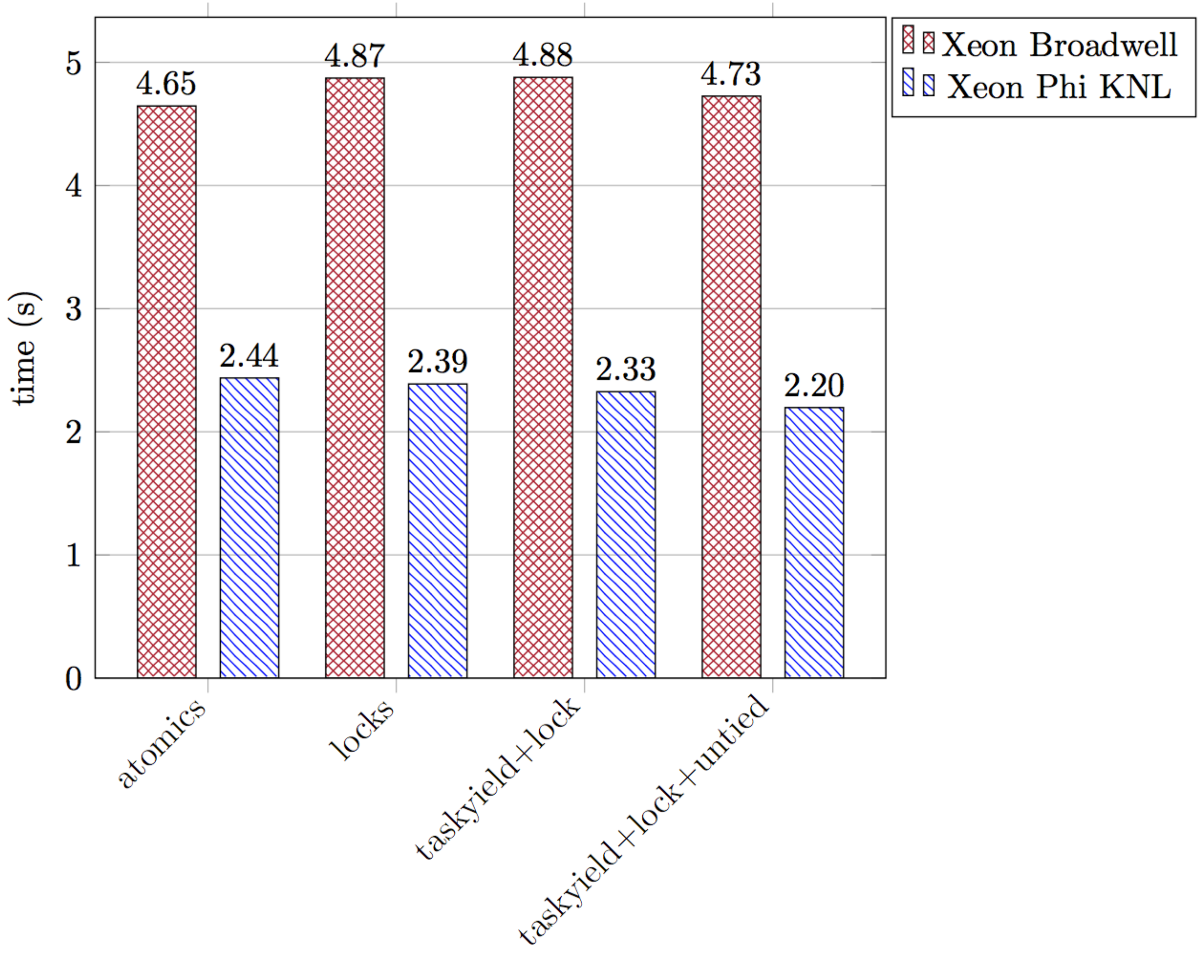
```
void force_calculation(node target, node source)
{
    int locked = 0;
    while (!locked)
    {
        locked = omp_test_lock(&target->lock);
        if (!locked)
        {
            #pragma omp taskyield
        }
    }

    // caculate or approximate force
    ...

    omp_unset_lock(&target->lock);
}
```

Atomically updating values

- Alternatively can atomically update values instead of locking entire node
- Four atomics per node update (task)
- Which is better locks or atomics? It depends
- On KNL atomics performed worse, on Xeon CPU depends if we can keep lock contention low
- Can lower lock contention with less work per node



Using different lock implementations

- Can specify in OpenMP which lock implementation to use
- First supported in Intel OpenMP - still not present in GCC (7.2)
- Can use locks that are better for high contention and/or speculative locks
- Default lock implementation worked best in miniFMM, all other combinations resulted in poorer performance

```
omp_lock_t lock;
omp_init_lock_with_hint(&lock,
  omp_lock_hint_<type>);

omp_lock_init_none
omp_lock_init_contended
omp_lock_init_uncontended
omp_lock_init_speculative
omp_lock_init_nonspeculative
```

Commutative dependencies

- Commutative dependency type specifies tasks can run in any order regardless of when they were generated
- Feature in OmpSs
- Would mean entire method could be implemented using task dependencies – allows for fine-grained synchronisation between stages
- But we would still suffer from starvation problem with one thread generating tasks

```
#pragma omp task depend(inout: target)
approximate_force(target, source)
```

↓

```
#pragma omp task depend(commute: target)
approximate_force(target, source)
```

Performance comparison overview

- OpenMP implementations: Intel (17.2), GCC (6.3), Cray (8.5.8), BOLT
- Programming models: OpenMP, OmpSs, CILK, TBB
- Also compared to data-parallel implementation where list of interactions are collected and then performed in a loop over the target nodes
- Typical problem size ~O(10^6) particles with maximum 500 particles per node

Hardware

Broadwell

- **2x Intel Xeon** E5-2699 v4 2.20 GHz
- 2 Sockets
- 22 cores per socket
- Up to 2 threads per core
- 256-bit width vectors

KNL

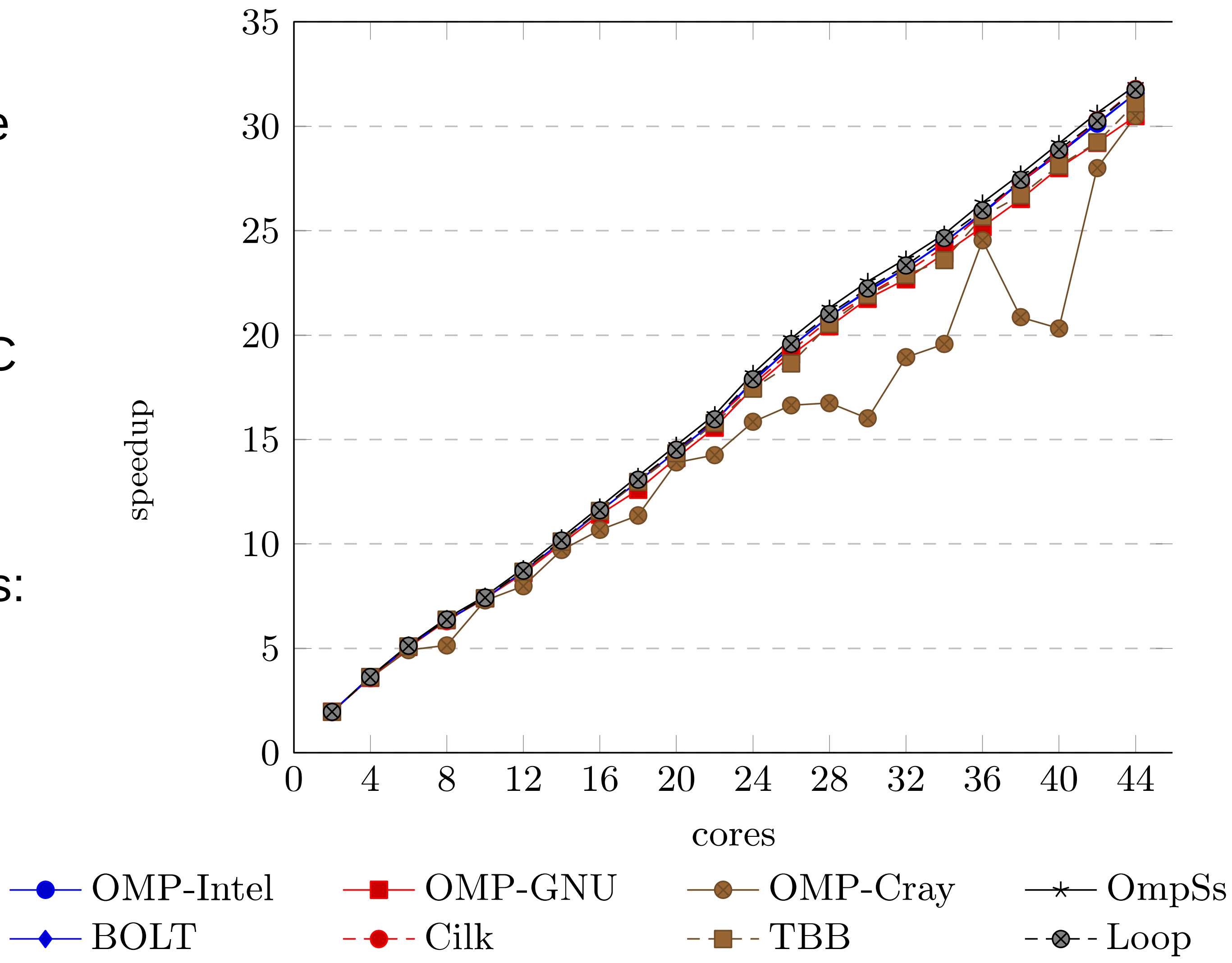
- **Intel Xeon Phi** 7210 1.30 GHz
- 64 cores
- Up to 4 threads per core
- 512-bit width vectors

Skylake

- **2x Intel Xeon** Gold 6152 2.10 GHz
- 2 Sockets
- 22 cores per socket
- Up to 2 threads per core
- 512-bit width vectors

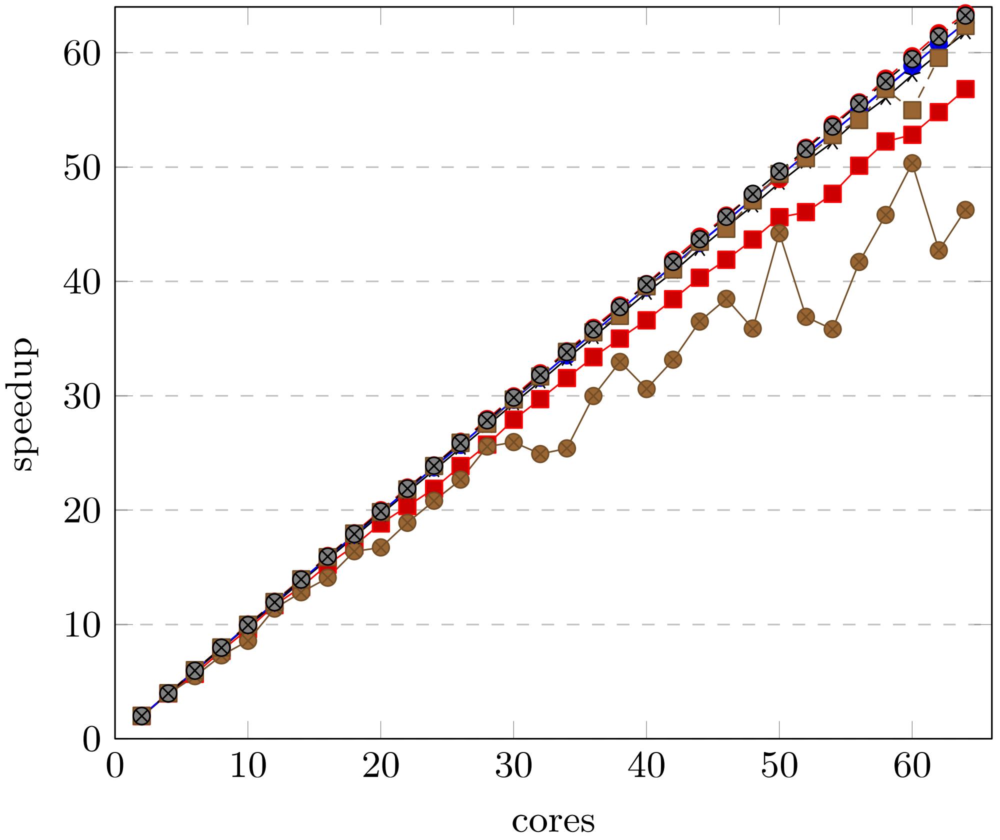
Results – Dual socket 22-core Broadwell

- Most OpenMP implementations, CILK, TBB, and OmpSs scale well and are close to data-parallel algorithm
- Intel runtimes (OpenMP, CILK, TBB) and OmpSs perform best whilst Cray and GCC lag behind
- Can be explained by measuring time outside of computational work, at 44 cores:
  - Intel 2.01%
  - GNU 8.31%
  - Cray 9.13%



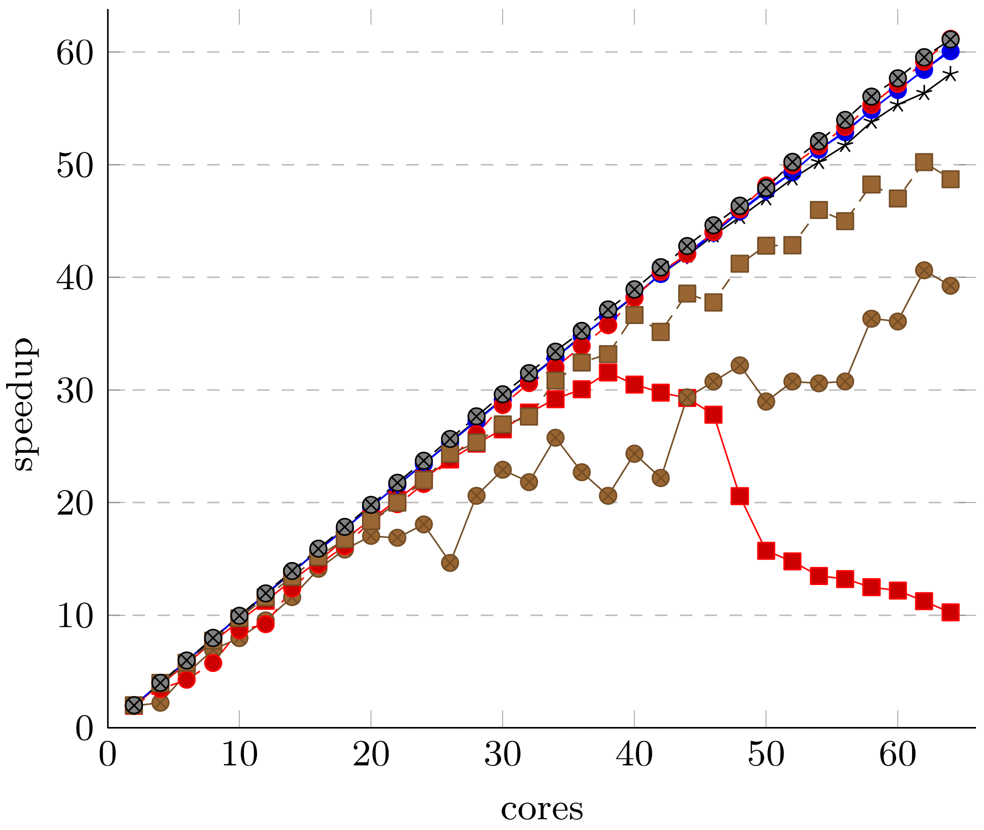
Results – 64 core KNL

1 thread per core

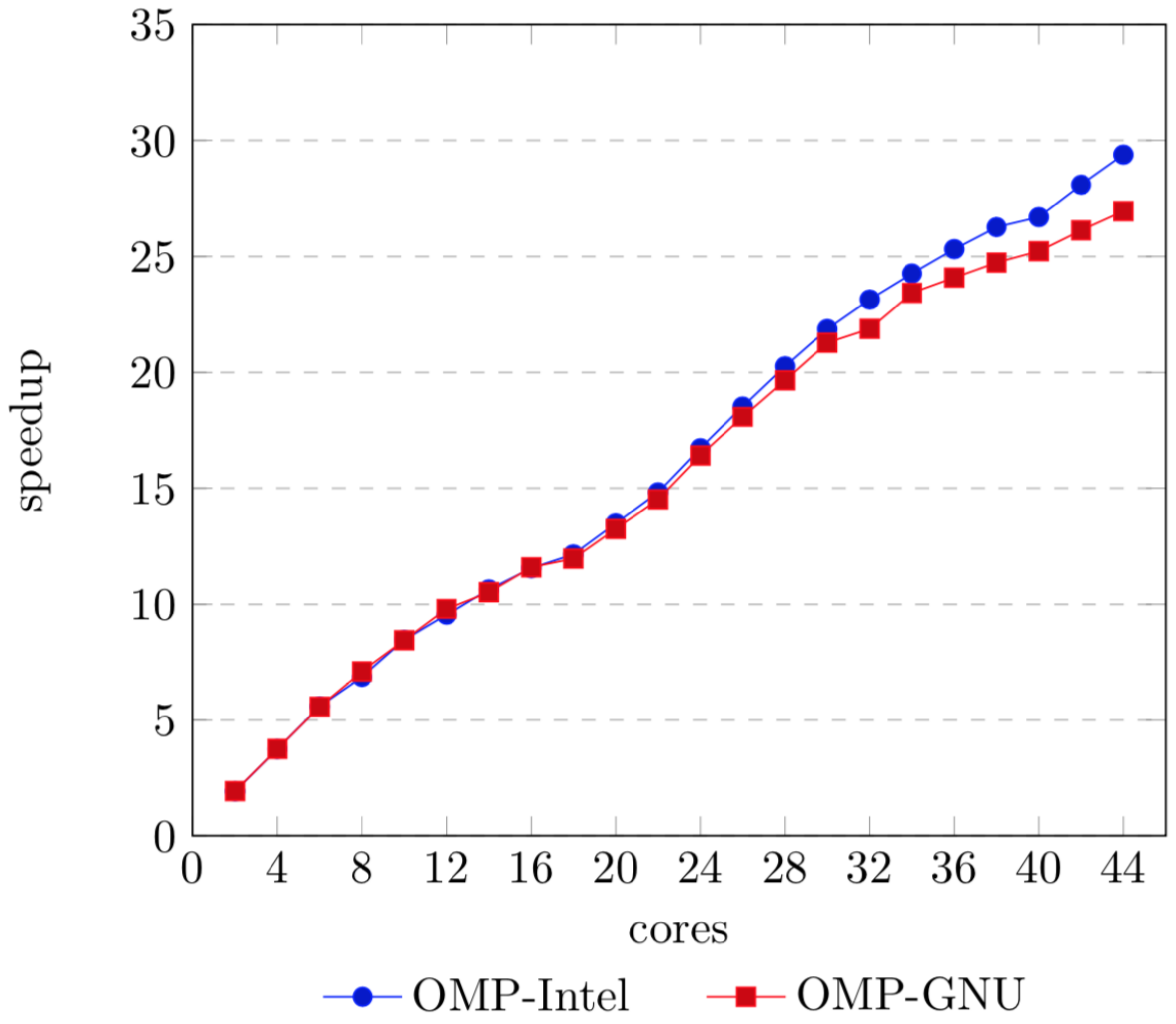


- Data-parallel code slightly outperforms task-parallel implementations
- Good OmpSs performance required changing scheduler to use queue per thread
- Performance **degrades** >~120 threads using GCC

4 threads per core



Results – Dual socket 22-core **Skylake**



Summary

- Tasks can significantly reduce lines of code whilst achieving good performance
- Difficult to express parallelism in irregular methods like FMM using current OpenMP task constructs – future changes in OpenMP could remedy this
- In the meantime alternatives to task dependencies exist
- Most programming models and implementations achieve good scaling/performance until scaling to high thread counts

Publications

Pragmatic Kernels, and Mini-apps including TeaLeaf, CloverLeaf, miniFMM, and SNAP
https://github.com/UK-MAC/
https://github.com/UoB-HPC/

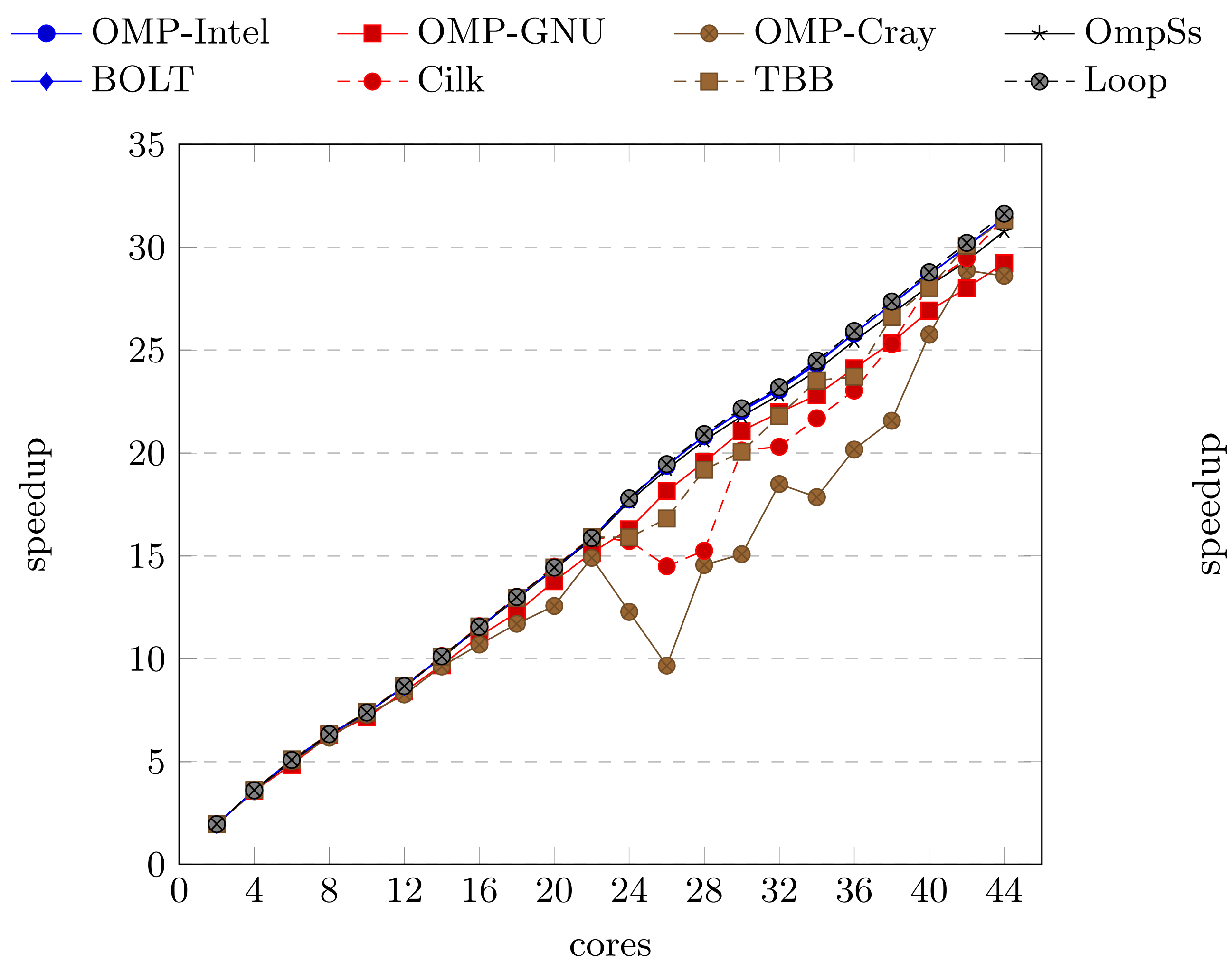
On the performance of parallel tasking runtimes for an irregular fast multipole method application
Atkinson, Patrick and McIntosh-Smith, Simon

Assessing the performance portability of modern parallel programming models using TeaLeaf
Martineau, Matt, McIntosh-Smith, Simon, and Gaudin, Wayne

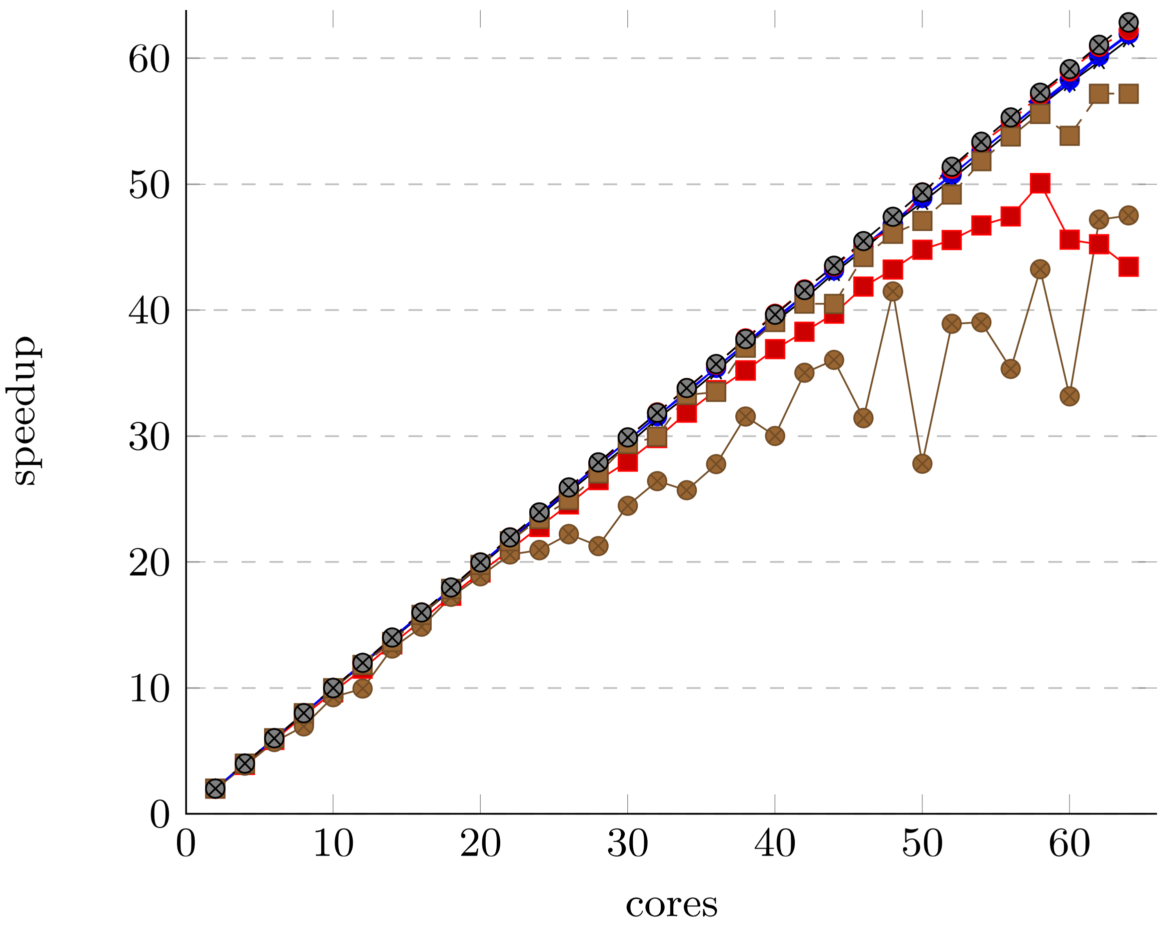
Many-core Acceleration of a Discrete Ordinates Transport Mini-app at Extreme Scale
Deakin, Tom, McIntosh-Smith, Simon N, and Gaudin, Wayne

The Productivity, Portability and Performance of OpenMP 4.5 for Scientific Applications Targeting Intel CPUs, IBM CPUs, and NVIDIA GPUs
Martineau, Matt and McIntosh-Smith, Simon

Extra slides



1 threads per core Broadwell



2 threads per core KNL