Locality-Aware Task Management for Unstructured Parallelism: A Quantitative Limit Study

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Limits in technology scaling, power, and complexity
- Parallelism now the norm to obtain sustainable performance

More cores are being packed on the same die
- Mainstream server processors contain 8 cores (16 threads)
- 61 core co-processors already available in the market

More cores increases memory demand
- On-chip cache hierarchies are getting deeper and more complex
More Cores $\rightarrow$ Locality Matters More

- NUMA effects prevalent on a single chip
  - **Performance**: remote cache and memory accesses cause significantly higher latency
  - **Energy**: moving a word of data consumes up to 20x energy than an arithmetic op on that word [SC’09]

- Data access locality should be exploited
  - Avoid remote cache and memory accesses
  - Reduce execution time and energy consumption

Locality on Task-Based Systems

- Task-based programming systems (e.g., Cilk, OpenMP, TBB)
  - A program is broken down into small tasks
  - Runtime schedules tasks across task queues for execution
  - Once a thread runs out of tasks, it may steal from other threads

![Diagram of task queues and memory hierarchy](image-url)

- Task Queues
- Memory

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Making Scheduler Locality-Aware

- To capture locality on a task-based system
  - The *scheduling algorithm* should be locality-aware

- Scheduler performs two things
  - *Group a set of tasks* to execute on the same core
  - Given those groups, determine the *execution order*

- Perform *grouping* and *ordering* in a locality-aware fashion

![Diagram showing task scheduling and core allocation]

- **Task Scheduler**
  - C0
  - C1

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Making Scheduler Locality-Aware

- Exact scheduling logic depends on the parallelism model

1. Structured parallelism (= task-parallel systems)
   - Explicit data/control dependencies exit across tasks
   - Relatively easy to capture locality
     - Group producers and consumers
     - Follow the dependency order

2. Unstructured parallelism (= data-parallel systems)
   - No dependency exists (e.g., parallel for-all)
   - Lack of dependency info = larger solution space
   - Complex cache hierarchies also a challenge
   - Capturing locality is hard, remains largely unsolved
Propose a systematic approach to exploit locality
1. Use a graph-based locality analysis framework
2. Generate offline schedules that are optimized for target

Perform limit study to quantify the potentials
- Simulate 3 different multicore designs
- Scale up to 1024 cores

Conduct a thorough scheduler design space exploration
- Capture the potentials in a practical setting
- Provide a guideline for future scheduler implementations

Show stealing can be made locality-compatible
Motivation

Locality-Aware Task Scheduling
  - Graph-Based Locality Analysis
  - Recursive Scheduling

Performance Results

Locality-Aware Task Stealing

Summary
Unstructured Parallelism

A parallel section = (1) *task function* and (2) *task space*
- Task = bundle of a coordinate and the task function
- Execute = invoke the task function with the coordinate as the argument

No dependencies among tasks
- A task may execute on any thread, any time, without affecting correctness
- A scheduler may arbitrarily group and order tasks

Challenge
- Too many ways to group/order tasks
- Complexity of the underlying cache hierarchy

```c
void conv_task(int x_pos, int y_pos);
```

Task Function Signature

![2-D Task Space](image)
1. Profile each workload to collect read/write sets for each task
2. For each parallel section, construct a task sharing graph
3. Perform grouping and ordering to understand inherent locality

**Graph-Based Locality Analysis**

```
mmm Task Sharing Graph (Partial)
```

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```
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```

```
0  [Task (task id)]

Sharing

Vertex Weight [Task size (# dynamic instrs)]

Edge Weight [# cache lines shared]
```
**Locality Implications: Task Grouping**

- Dispatch a group of tasks at a time
  - Amortize scheduling overheads
  - Capture data reuse across tasks

- **Partition** the task sharing graph s.t.
  - The sum of *edge weights* within each group is maximized (maximize locality)
  - Equalize the sum of *vertex weights* for each group (load balance)
  - Task group should be sized so that the working set fits in cache (from trace)

- NP-hard
  - Use a heuristic graph partitioner (METIS)
Locality Implications: Task Ordering

- Order tasks to minimize the *distance between reuses* of shared data
  - Improves temporal locality
- Obtain a *traversal order* of vertices s.t. it minimizes reuse distance
- NP-hard
  - Use Maximum Spanning Tree (MST) construction
    - Accumulate the history of scheduled tasks and pick the next task with maximum sharing
- Task groups can be similarly ordered
Perform task grouping and ordering in a *recursive fashion*
- Start from bottom: generate task groups and order them
- Recursively apply the process, targeting one level up in the hierarchy each time

Results in a hierarchy of task groups
- Entire stack of task groups stay *resident* across the entire cache hierarchy
Agenda

- Motivation
- Locality-Aware Task Scheduling
  - Graph-Based Locality Analysis
  - Recursive Scheduling
- Performance Results
- Locality-Aware Task Stealing
- Summary
Experiment Settings

- Represent various approaches to many-core designs
  - Simulate three different 32-core designs
  - Scale up to 1024 cores (Futuristic Processor)

Throughput Processor
(e.g., Intel Xeon Phi)
(All-Private Cache Hierarchy)

Tiled Processor
(Tree-Based Cache Hierarchy)

Futuristic Processor
(All-Private Cache Hierarchy)
Experiment Settings (contd.)

- Generate recursive schedules for each architecture, offline
  - Static scheduler reads in the schedule and populates queues

- Compare against different schedules
  - Recursive schedule (upper bound)
  - Random schedule (random bound)
    - Randomly group and order tasks into # threads
  - Baseline schedule (state-of-the-art)
    - Split the single-thread schedule into # threads
    - Exploits sequential locality across parallel execution [SPAA’07]

- Quality metric of a schedule: sum of the execution time of tasks
  - Will talk about the impact of load imbalance later

- Insights were similar
  - Start with Throughput Processor, and contrast the others

Baseline captures some locality over random
Recursive scheduling significantly improves performance
- 1.41x over baseline (both L1 and L2 misses were reduced)
- For gjk and brmap, baseline was good enough

Much room for locality-aware task scheduling
- Locality will be even more important on larger scales
Memory Hierarchy Energy Reduction

- Memory hierarchy energy from the model [Micro’10]
  - Activity counts for memory hierarchy beyond L1 + CACTI
  - Reduction in cache misses translates into significant energy savings
    - 55% lower than random, and 47% lower than baseline

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Disable the ordering component of recursive scheduling
- Group tasks into L2 granularity + subgroup into L1
- Use random ordering throughout

Grouping alone can capture significant locality
- Ordering provides limited benefit, once task grouping is determined

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Single-Level Schedules

- Perform grouping and ordering at a single level
  - L1 or L2-sized task groups with MST task ordering
  - Random ordering across groups

- Due to flat cache hierarchy, single level schedules can capture significant locality

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Recursive scheduling provides significant performance improvement
- 1.40x over random, 1.35x over baseline
- Recursive scheduling can be generically applied to various cache hierarchies

Unlike the Throughput Processor
- Improvement due to ordering further diminished
- Multi-level schedules provided larger gains

Tree-based hierarchy: should match task group hierarchy to cache hierarchy

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Futuristic Processor Results

- Scale # cores from 32 to 1024
  - Compare the performance of recursive schedules against random schedules

- Benefits from locality-awareness increases
  - Average 1.27x speedup (32 cores) to 1.61x speedup (1024 cores)
  - Magnitude depends on the workload pattern (e.g., hj and smvm w/ L1 sharing)

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Summary:
Locality-Aware Task Scheduling

- Large potential exists for locality-aware task scheduling (both performance + energy)
  - All 3 systems benefitted from recursive scheduling
  - Only increases with larger core count

- Guidelines for practical schedulers
  - Grouping tends to be more effective than ordering
  - If only one, implement recursive grouping
  - For (mostly) private hierarchy, single-level schedule at last level is effective
Motivation
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Performance Results
Locality-Aware Task Stealing
Summary
Locality Analysis of Task Stealing

- Sources of dynamic load imbalance
  - Context switching due to multiprogramming
  - “Intelligent” runtimes share a chip
    - Generate schedules assuming they own the entire chip: destructive oversubscription

- Task stealing should actively redistribute tasks
  - Locality exploited in the original schedule can be lost

- Exploiting locality while stealing
  - Preserve the locality exploited in the original schedule
  - Honor the specified task groupings and orderings
Making Stealing Locality-Aware: Recursive Stealing

- Match the queue hierarchy to the cache hierarchy
  - Store order = group order specified by the recursive schedule
  - When transferred across levels, a task group is broken down

- Recursively steal a task group at a time
  - Up to 2.0x task performance improvement for stolen tasks (Throughput Processor)
Agenda

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  - Recursive Scheduling
- Performance Results
- Locality-Aware Task Stealing
- Summary
Summary

- Provided a systematic approach to exploit locality from unstructured parallel tasks
  - Graph-based analysis framework + offline scheduler

- Limit study demonstrates significant potential
  - Performance/energy benefits on 3 different systems
  - Benefits only increase with larger core count

- Design space exploration
  - Grouping tends to be more effective than ordering
  - For (mostly) private hierarchy, single-level schedule at last level is effective

- Stealing can be made locality-compatible
  - By honoring the original schedule while redistributing