Distributed Continuation Stealing is More Scalable than You Might Think

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Dynamic Load Balancing on Distributed Memory

- **Dynamic load balancing** is particularly important for irregular algorithms
  - e.g., sorting, sparse matrix arithmetic, tree-based algorithms, AMR, ...
- Hardware is becoming massively parallel → **Manual load balancing is getting harder**
  - intra-/inter-node, many-core, deep cache hierarchy, NUMA, ...
- **Work stealing** is a popular algorithm for automatic load balancing by the runtime
  - Only when a processor becomes idle, it attempts to steal work from another processor

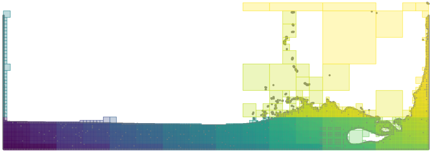


Fig. Fluid simulation (SPH)

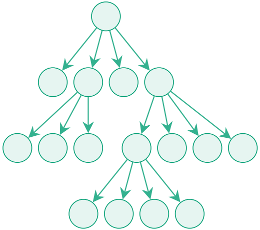


Fig. Unbalanced Tree

Task Parallelism (Fork-Join Parallelism)

- Spawn (fork) a concurrent thread and join its completion
  - threads can be created recursively → well suited to divide-and-conquer algorithms

```
thread th = spawn([=]{ A(); });
B(); // A() and B() are executed concurrently
th.join(); // ensures completion of A()
```

- General parallel execution model for many algorithms
  - e.g., matrix arithmetic, FFT, sorting, dynamic programming, game tree search, space-partitioning tree, N-body, ...
  - Adopted by many runtimes: Cilk, Intel TBB, Java fork/join, OpenMP, ...
- A bunch of threads ($\gg$ # of cores) can be created
  - The underlying runtime performs dynamic load balancing

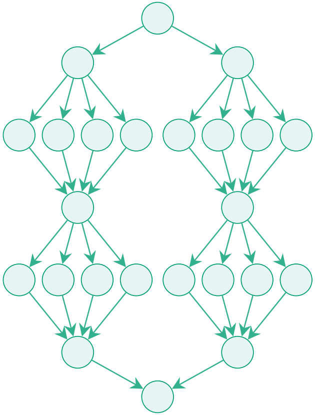
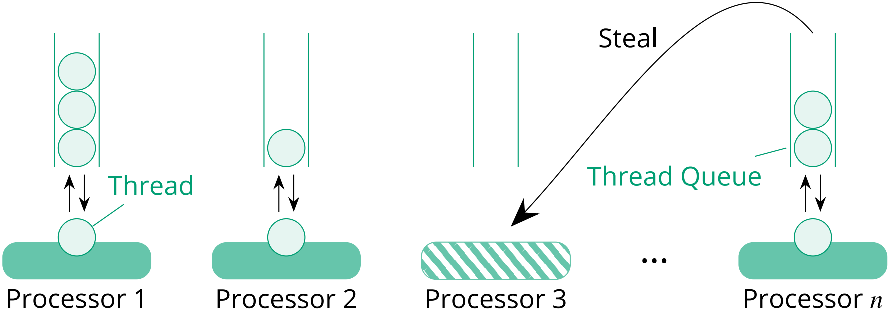


Fig. Task dependency graph

Work Stealing [Blumofe and Leiserson, JACM '99]

- Widely used scheduling strategy for task-parallel programs
- Each processor has its own **thread queue**
- A processor pushes stealable threads to its thread queue
- A processor pops a thread from its local queue when the current thread is completed
- When the local queue is empty, it steals a thread from a randomly selected processor



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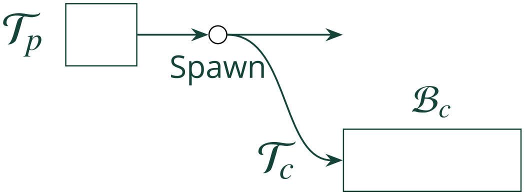

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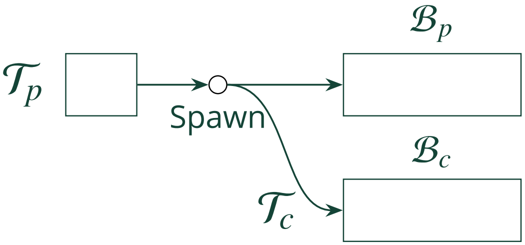

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Thread 𝒯_p:
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    ℬ_p;
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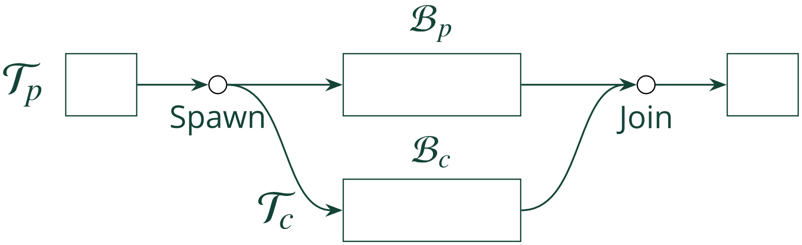

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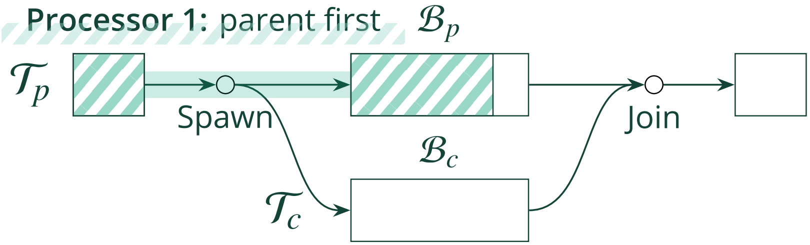

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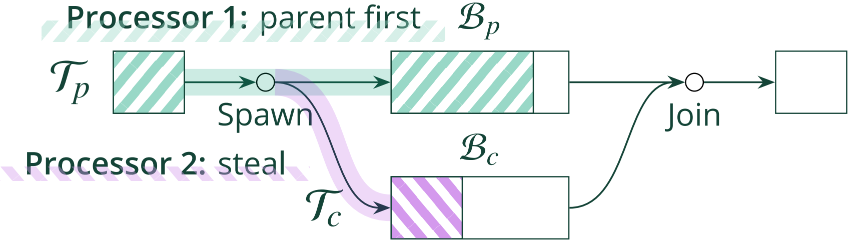

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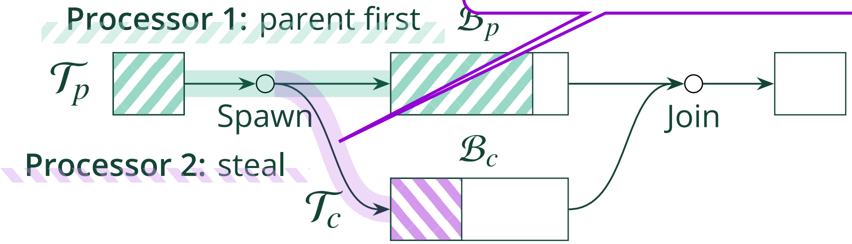
```

The newly created child is stolen
→ **Child stealing**



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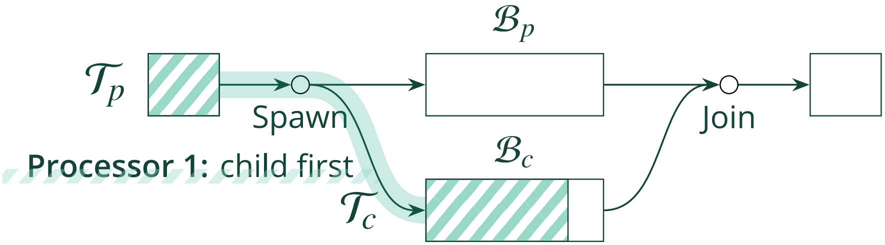

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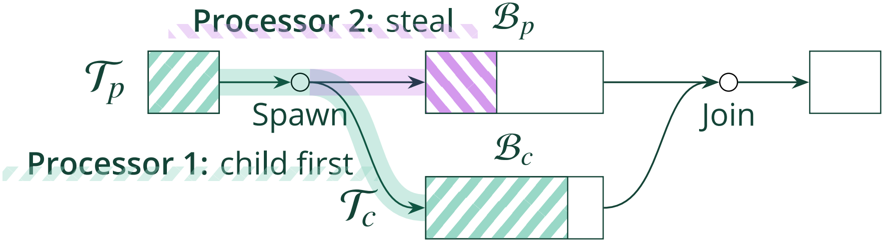

What is Continuation Stealing?

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Thread 𝒯_p:
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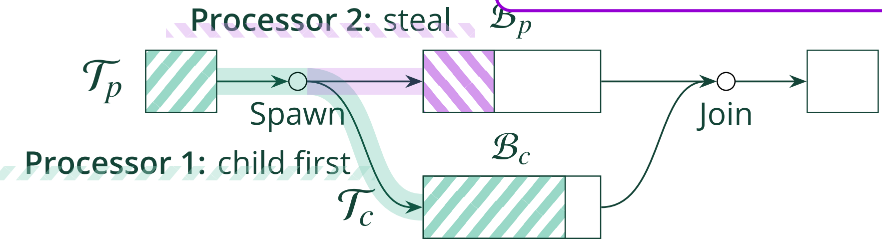
The parent's continuation is stolen
→ **Continuation stealing**



Why We Consider Continuation Stealing is Better

- Many shared-memory runtimes (e.g., Cilk) use continuation stealing because of its efficiency
- Good characteristic: **Continuation stealing preserves the serial execution order**
  - i.e., the execution order of programs with spawn/join keywords removed
  - **Ordinary function call:** execute the called function $\longrightarrow$ its continuation
  - **Continuation stealing:** execute the spawned thread $\longrightarrow$ its continuation
- Because of this execution order, continuation stealing is unlikely to be blocked at join
  - Later, I'll explain why

Continuation Stealing on Distributed Memory

- However, most distributed work-stealing runtimes use child stealing

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2. **Continuation stealing is less efficient than child stealing** because a whole call stack needs to be copied across nodes

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  1. It is **difficult to implement continuation stealing as a library** with unmodified C/C++ compilers
  2. **Continuation stealing is less efficient than child stealing** because a whole call stack needs to be copied across nodes
- The first concern was addressed by [Akiyama and Taura, HPDC '15]
  - Efficient RDMA-based continuation stealing by copying call stacks across nodes

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- The first concern was addressed by [Akiyama and Taura, HPDC '15]
  - Efficient RDMA-based continuation stealing by copying call stacks across nodes
- The second concern has not previously been addressed
  - No performance comparison against child stealing or any other existing runtimes

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- The first concern was addressed by [Akiyama and Taura, HPDC '15]
  - Efficient RDMA-based continuation stealing by copying call stacks across nodes
- The second concern has not previously been addressed
  - No performance comparison against child stealing or any other existing runtimes
- **This paper suggests that the second assumption is not true**

Contributions

Technical Contribution:

- Efficient **join** implementations over **RDMA**, which were not covered by previous work
  - in order to reveal the full potential of continuation stealing

Experimental Results:

- Despite a small increase in steal latency, **continuation stealing often outperforms child stealing** overall
- **Even compared with existing runtimes, continuation stealing is reasonably fast** (showing great scalability to **more than 100k cores**)
- As well as steal policies, **different join policies largely affect performance** particularly for programs with a complicated dependency pattern

Continuation stealing is beneficial even on distributed memory!

Outline

Background

Joining Threads over RDMA

Evaluation

- Performance Analysis of Various Scheduling Policies (Synthetic Benchmark)
- Scalability Study with State-of-the-Art Systems (UTS Benchmark)
- Thread Migration Capability and Futures (LCS Benchmark)

Conclusion and Future Work

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Child Stealing vs. Continuation Stealing on distributed memory

	Child Stealing	Continuation Stealing
Easy to implement?	Yes	Not so easy
Representation of a stealable task	Function pointer + arguments	Call stack
Preserves serial execution order?	No	Yes
Likely to efficiently resolve join?	No	Yes

Child Stealing vs. Continuation Stealing on distributed memory

Continuation stealing requires **thread migration** (without compiler support), which is nontrivial to implement (but possible [Akiyama and Taura, HPDC '15])

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Child Stealing vs. Continuation Stealing on distributed memory

Continuation stealing needs to copy the call stack, which is typically larger than a function pointer and its arguments → **Larger steal cost?**

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Child Stealing vs. Continuation Stealing on distributed memory

Continuation stealing preserves the serial execution order (the order without spawn/join primitives) → good theoretical bounds are known

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Child Stealing vs. Continuation Stealing on distributed memory

Continuation stealing is considered more efficient for resolving join → **Next slide**

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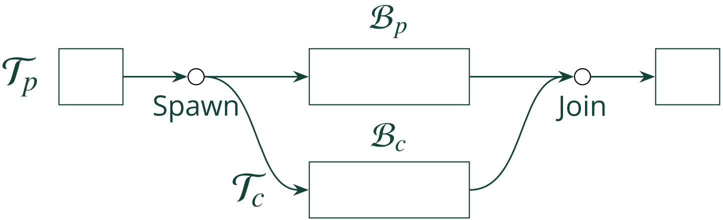
Child Stealing → Joins are Likely to be Blocked



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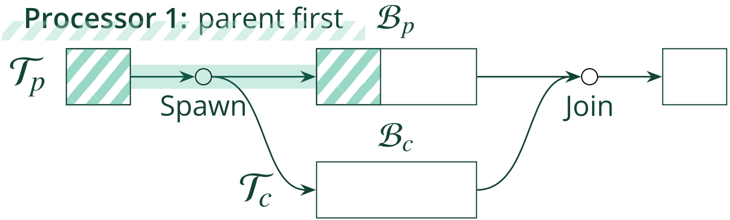

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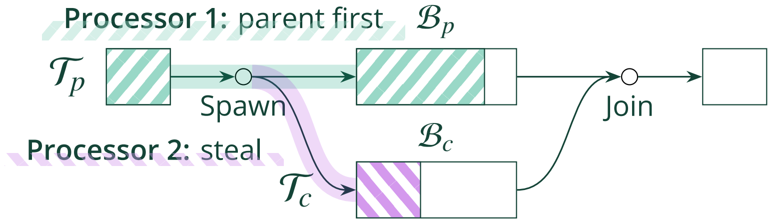

Execution of the child $\mathcal{B}_c$ is delayed compared to the parent $\mathcal{B}_p$

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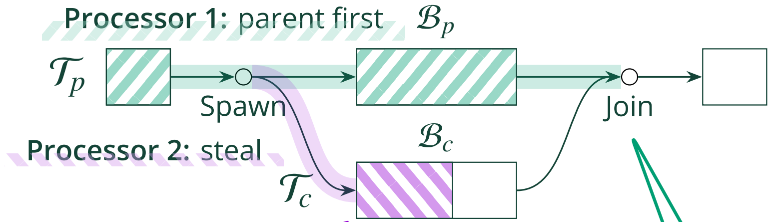
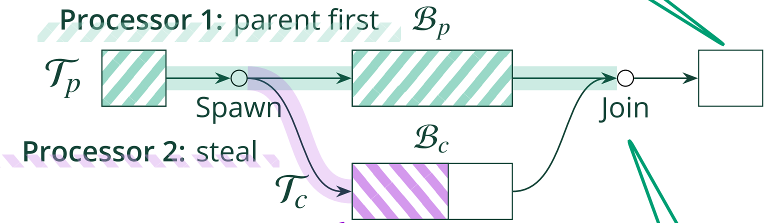


Execution of the child $\mathcal{B}_c$ is delayed compared to the parent $\mathcal{B}_p$

The parent is likely to reach the join earlier
→ The parent is **likely to be blocked at join**

Child Stealing → Joins are Likely to be Blocked

The parent can be resumed when the child is completed,
but processor 1 may be busy when the join is resolved
→ **execution of the continuation of the join can be delayed**



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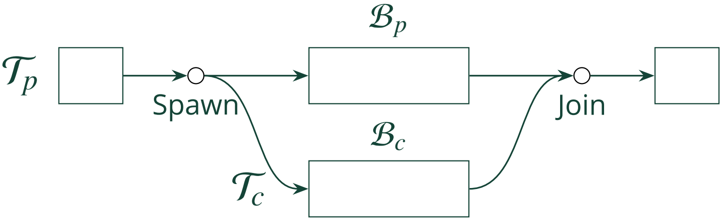

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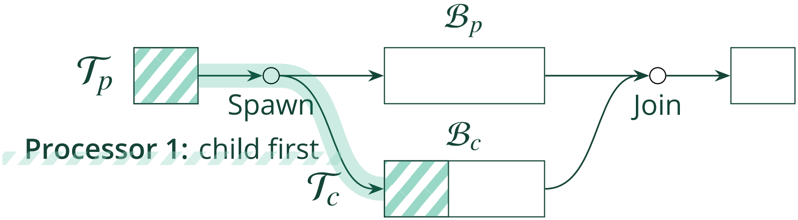

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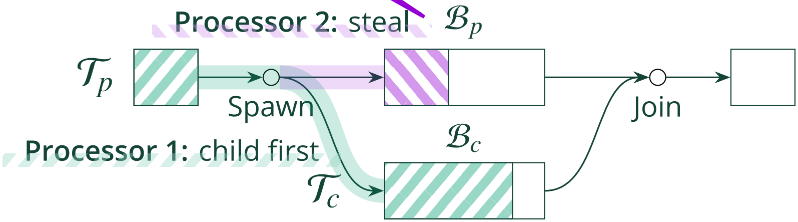

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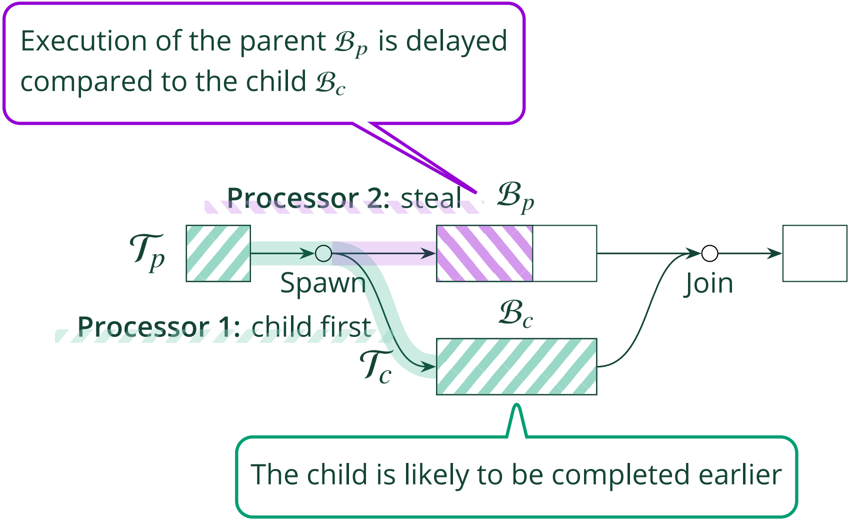

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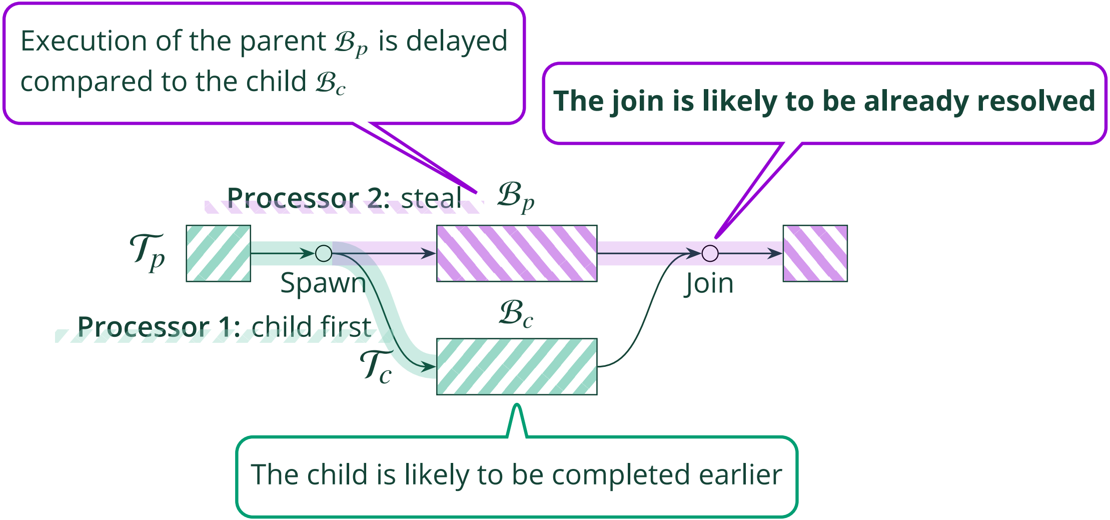

Previous Work – Uni-Address Threads [Akiyama and Taura, HPDC '15]

- Efficient RDMA-based continuation stealing without compiler modification
- Basic idea: copy thread stacks to the same virtual address before threads are executed
- Good scalability to 4096 cores was reported
- **No comparison with child stealing or existing distributed task-parallel runtimes**

We still don't know whether distributed continuation stealing is worth implementing

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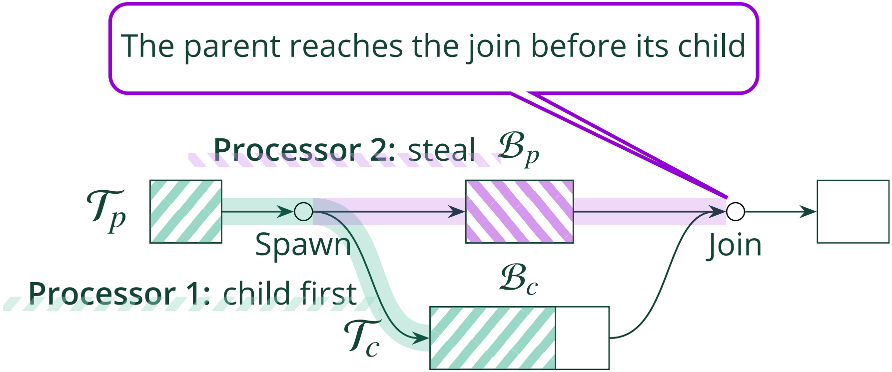
Performance Improvements for Join

- To evaluate the full potential of continuation stealing, we need to carefully design **join** implementations, which were not well considered in previous work
- We introduced two improvements for join
  1. **How to efficiently resume the continuation of the join when blocked**
  2. How to efficiently free memory needed for join remotely (see the paper)
- In this talk, we will explain the first improvement

Joining Strategy – Overview

- In general, there are two strategies to resolve a join in fork-join programs
  1. **Stalling join:** across a join, the executing processor is the same (e.g., Intel TBB)
  2. **Greedy join:** the processor who runs the parent or the child, whichever reaches a join point later, executes the continuation of the join (e.g., Cilk)
- Theoretically, **greedy join** is considered better than **stalling join**
- In practice, **greedy join** is more difficult to implement because it involves thread migration
- The previous work [Akiyama and Taura, HPDC '15] uses **stalling join** strategy
- We implemented **greedy join** strategy by using RDMA atomic operations

Stalling Join (Previous Implementation)



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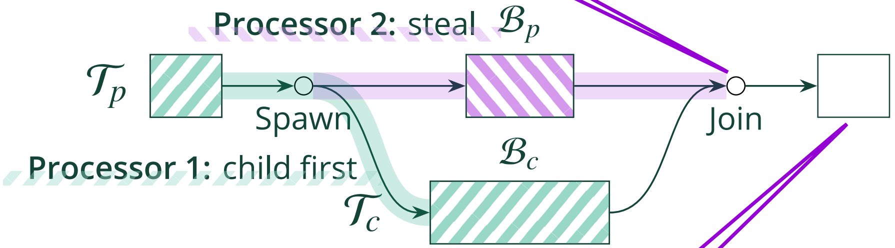

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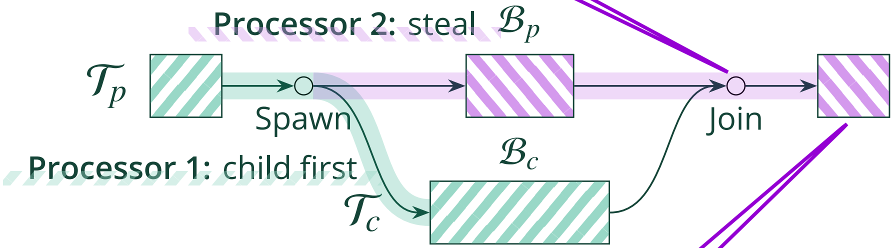

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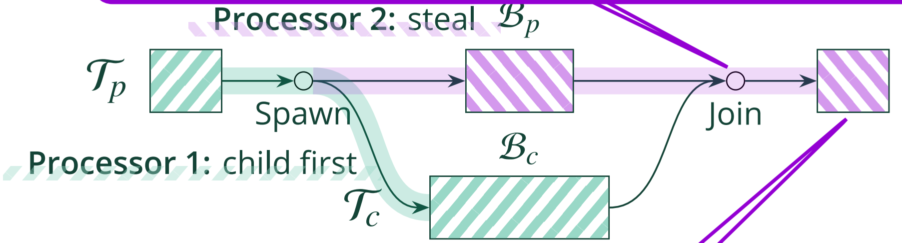
However, **processor 2** may be busy when the join is resolved
→ **execution of the continuation of the join can be delayed**



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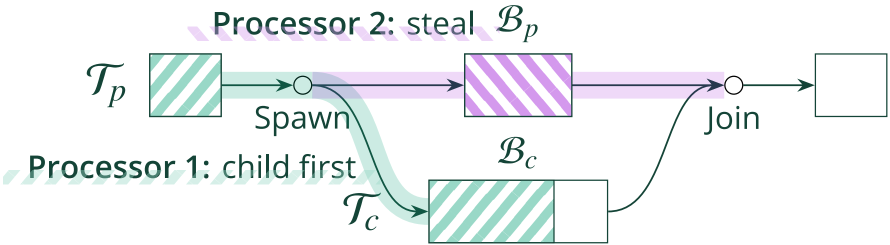

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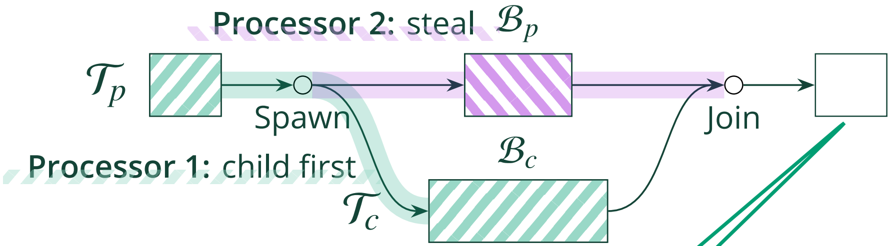

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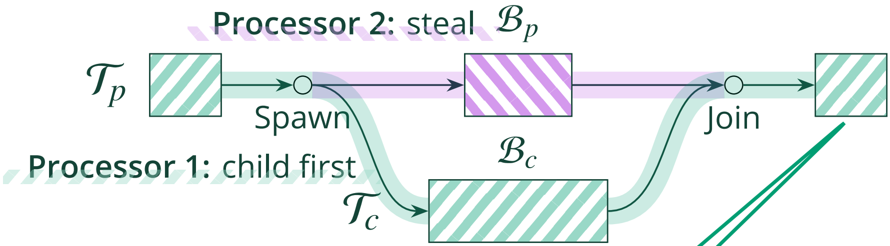

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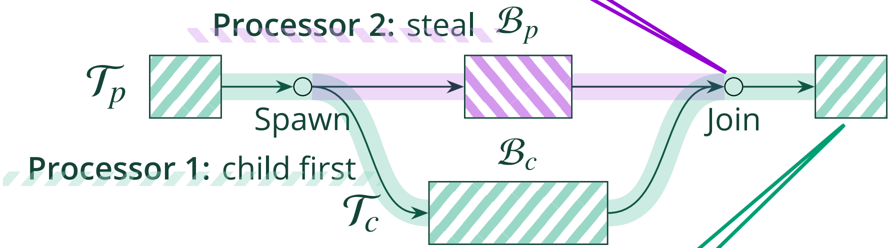
Greedy Join (Our Improvement)

The parent thread needs to be migrated from **Processor 2** to **Processor 1** at join



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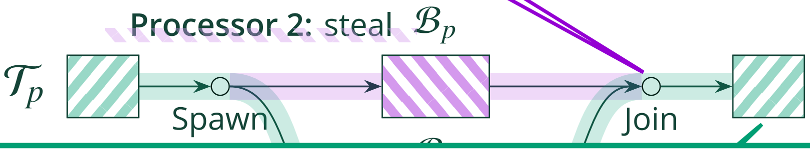

We devised an efficient RDMA-based implementation of **greedy join** in a lock-free manner by utilizing **RDMA atomic operations**

If the child thread is completed later, the continuation of the join is immediately resumed by **Processor 1**

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Evaluation – Overview

Research questions:

1. How does continuation stealing perform compared with child stealing?
2. Is it practical to use continuation stealing in distributed task-parallel runtimes?
3. How important is thread migration (like greedy join) on distributed memory?

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Summary of our findings:

1. Despite a small increase in steal latency (only less than 20%), **continuation stealing often outperforms child stealing by efficiently resolving joins**
2. **Even compared with existing bag-of-tasks runtimes (without joins), our system is reasonably fast** (96.4% parallel efficiency on **110,592 cores** in UTS benchmark)
3. **Lack of thread migration capability (at either fork or join) leads to bad performance** when we intensively use threads as futures (in LCS benchmark)

Experimental Settings

- We implemented various strategies over MPI-3 RMA in a C++ library developed in the previous work (MassiveThreads/DM [Akiyama and Taura, HPDC '15])
- Two variants of continuation stealing (**stalling** and **greedy** join)
- Two variants of child stealing (RtC and Full), which mimic prevalent implementations
  - Only the one with better performance (Full) is shown in this presentation

Experimental environment:

- ITO-A: **ITO supercomputer (subsystem A)** at Kyushu University (up to 256 nodes)
  - Intel Xeon Gold 6154 (36 CPU cores/node), InfiniBand EDR 4x (100 Gbps), Open MPI v5.0.x
- Wisteria-O: **Wisteria/BDEC-01 Odyssey** at the University of Tokyo (up to 2304 nodes)
  - Fujitsu A64FX (48 CPU cores/node), Tofu Interconnect-D, Fujitsu MPI

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Synthetic Benchmark

- Recursive parallel-for benchmark (RecPFor)
- Two-way divide-and-conquer + parallel for loop at each recursion
- Common pattern for many divide-and-conquer algorithms
  - e.g., quicksort, tree construction (kdtree, decision tree)
- Each leaf task spins for 10 μs ($M = 10\mu s$)

```
RecPFor(int n) {
  if (n == 1) {
    compute(M); // run for duration of M
  } else {
    for (int k = 0; k < 5; k++) {
      parallel_for (int i = 0; i < n; i++)
        compute(M); // run for duration of M
    }
    thread th = spawn([=] { RecPFor(n/2); });
    RecPFor(n/2);
    th.join();
  }
}
```

Synthetic Benchmark – Performance Analysis

- We profiled the execution of the RecPFor benchmark ($N = 2^{22}$)
- **ITO-A:** 576 cores (16 nodes), **Wisteria-O:** 1728 cores (36 nodes)

System	Steal Strategy	Time	# of Outstanding Joins	# of Steals (Successful)	Avg. Steal Latency (Successful)	Avg. Stolen Task Size
ITO-A	Cont. Steal (greedy)	**8.30 s**	**56876**	**474991**	31.6 μs	1845 bytes
	Cont. Steal (stalling)	8.33 s	72546	807097	30.4 μs	1790 bytes
	Child Steal	9.31 s	3208417	6038858	**29.3** μs	**55 bytes**
Wisteria-O	Cont. Steal (greedy)	**5.94 s**	**229154**	**1790018**	20.4 μs	1139 bytes
	Cont. Steal (stalling)	5.97 s	279035	3086034	20.6 μs	1156 bytes
	Child Steal	7.69 s	8602558	15704498	**19.9** μs	**55 bytes**

Synthetic Benchmark – Performance Analysis

Continuation stealing outperforms child stealing
(We will see a larger performance difference between stalling and greedy join in LCS)

System	Steal Strategy	Time	# of Outstanding Joins	# of Steals (Successful)	Avg. Steal Latency (Successful)	Avg. Stolen Task Size
ITO-A	Cont. Steal (greedy)	**8.30 s**	**56876**	**474991**	31.6 μs	1845 bytes
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Synthetic Benchmark – Performance Analysis

Child stealing incurs a much larger number of **outstanding joins**
→ **less parallelism available**

An **outstanding join** is a join that is blocked due to a steal event

System	Steal Strategy	Time	# of Outstanding Joins	# of Steals (Successful)	Avg. Steal Latency (Successful)	Avg. Stolen Task Size
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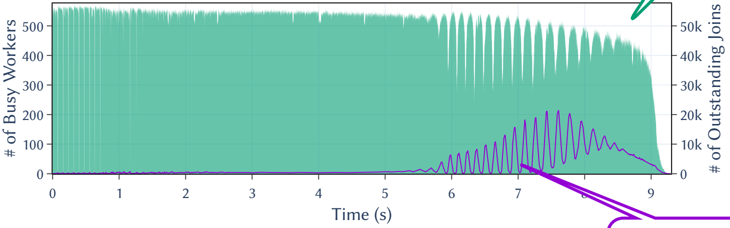
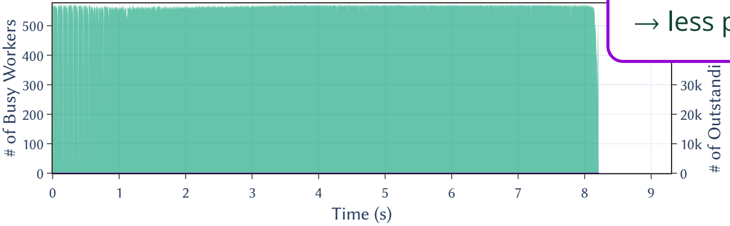
Synthetic Benchmark – Performance Analysis

Many idle workers

Child Steal:



Cont. Steal (greedy):



Many outstanding joins → less parallelism

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System	...g. Stolen Task Size
ITO-A	55 bytes
Wisteria-O	139 bytes
	156 bytes
	55 bytes

Synthetic Benchmark – Performance Analysis

- less parallelism $\rightarrow$ larger number of steals
- Greedy join is the most efficient, as it can immediately resolve outstanding joins

System	Steal Strategy	Time	# of Outstanding Joins	# of Steals (Successful)	Avg. Steal Latency (Successful)	Avg. Stolen Task Size
ITO-A	Cont. Steal (greedy)	**8.30 s**	**56876**	**474991**	31.6 μs	1845 bytes
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Synthetic Benchmark – Performance Analysis

- Cont. steal needs to copy the call stack → larger stolen task size
- Nevertheless, the steal latency is only less than 20% longer than child stealing

System	Steal Strategy	Time	# of Outstanding Joins	# of Steals (Successful)	Avg. Steal Latency (Successful)	Avg. Stolen Task Size
ITO-A	Cont. Steal (greedy)	**8.30 s**	**56876**	**474991**	31.6 μs	1845 bytes
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Synthetic Benchmark – Performance Analysis

- Cont. steal needs to copy the call stack → larger stolen task size
- Nevertheless, the steal latency is only less than 20% longer than child stealing

Despite a small increase in steal latency, continuation stealing has an overall performance benefit

System			# of		Avg. Steal	Stolen sk Size
ITO-A						5 bytes
	Cont. Steal (stalling)	8.33 s	72546	807097	30.4 μs	1790 bytes
	Child Steal	9.31 s	3208417	6038858	**29.3 μs**	**55 bytes**
Wisteria-O	Cont. Steal (greedy)	**5.94 s**	**229154**	**1790018**	20.4 μs	1139 bytes
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Outline

Background

Joining Threads over RDMA

Evaluation

- Performance Analysis of Various Scheduling Policies (Synthetic Benchmark)
- Scalability Study with State-of-the-Art Systems (UTS Benchmark)
- Thread Migration Capability and Futures (LCS Benchmark)

Conclusion and Future Work

Unbalanced Tree Search (UTS) Benchmark

- A widely used benchmark to measure the load balancing capability of runtime systems
- **X-axis:** the number of processes, up to 110,592 cores (2304 nodes)
- **Y-axis:** throughput of the benchmark (higher is better)
- **Our system could achieve 96.4% parallel efficiency on 110,592 cores**

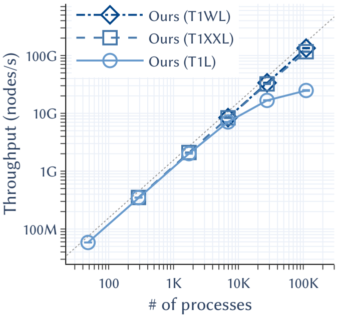

Fig. Result on Wisteria-O

Settings:

- UTS counts the number of all nodes in an unbalanced tree in parallel
- Throughput: the number of counted nodes per second
- Ideal throughput (the straight line) is calculated by serial performance
- Tree sizes: T1L < T1XXL < T1WL
- Cont. steal (greedy join)

Comparison with Existing Bag-of-Tasks Runtimes in UTS

- Also compared our runtime with existing systems on ITO-A (with InfiniBand)
- **Competitors:** three state-of-the-art work-stealing systems based on bag-of-tasks
  - Child stealing, **no join** primitive → global termination detection is needed
- Our system and SAWS [Cartier+, ICPP '21] → RDMA-based, good scalability
- Charm++ and X10/GLB → no RDMA, worse scalability

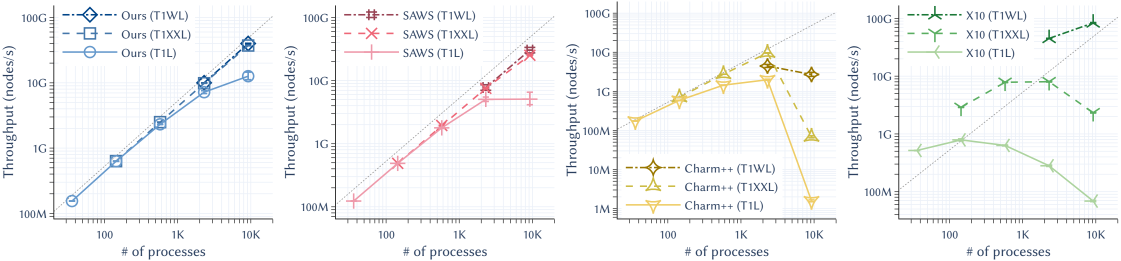

Fig. **Our Runtime System** Fig. SAWS Fig. Charm++ Fig. X10/GLB

Comparison with Existing Bag-of-Tasks Runtimes in UTS

- Also compared our runtime with existing systems on ITO-A (with InfiniBand)

Summarizing, our system

- Has more general synchronization (join) and thread migration capability
- Performs as well as or even better than bag-of-tasks counterparts

- Charm++ and X10/GLB → no RDMA, worse scalability

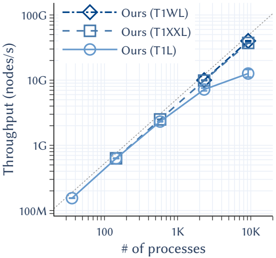

Fig. **Our Runtime System**

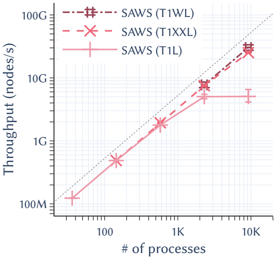

Fig. SAWS

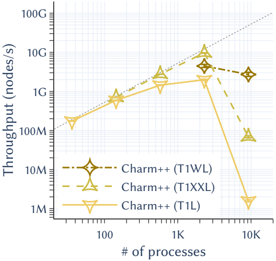

Fig. Charm++

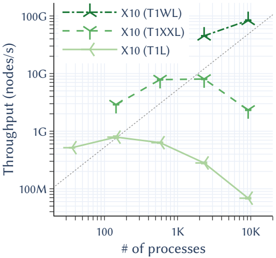

Fig. X10/GLB

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Preliminaries: Fork-Join and Futures

- Our thread implementation is not only for **fork-join** but also for **futures**
- **Fork-join:** a thread must be joined by its parent (parallelism is nested)
- **Future:** a thread (called future) can be joined at any point (not strictly nested)
- Our **longest common subsequence (LCS)** benchmark intensively uses futures
  - It combines recursive space decomposition and futures to represent true task dependencies
  - **Lack of thread migration capability easily falls into bad load balancing** in this benchmark

Results of the LCS Benchmark

- We compared three scheduling policies with different thread migration capabilities
- Child stealing: No thread migration
- Cont. Steal (stalling): Migration at **steal**
- Cont. Steal (greedy): Migration at **steal** + Migration at **join**
- **Lack of either migration capability led to much worse performance** (due to bad load balancing)

Tab. Execution times with 576 cores (16 nodes).

Size	**Cont. Steal (greedy)**	Cont. Steal (stalling)	Child Stealing
2^{18}	**0.569 s**	3.44 s	93.1 s
2^{22}	**45.9 s**	433 s	2.11×10^4 s

Settings:

- Run on 16 nodes of ITO-A
- Find an LCS length of N 1-byte characters (randomly generated)
- Serial cutoff size: 2^9

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Conclusion and Future Work

Summary

Our artifact is available at:

`https://github.com/s417-lama/cluster22-contsteal-artifact`

Conclusion:

- We introduced an efficient RDMA-based greedy join implementation
- Despite a small increase in steal latency, continuation stealing has an overall performance benefit in nested fork-join programs
- Thread migration (both continuation stealing and greedy join) is particularly important for programs with a complicated dependency pattern

Future Work:

- Integrate with PGAS to handle global data
  - Current system only allows function arguments and return values for data exchange
- Apply memory hierarchy-aware scheduling to improve data locality
  - e.g., Almost Deterministic Work Stealing (ADWS) **[Shiina and Taura, SC '19 and TPDS '22]**