Lessons Learned from Analyzing Dynamic Promotion for User-Level Threading

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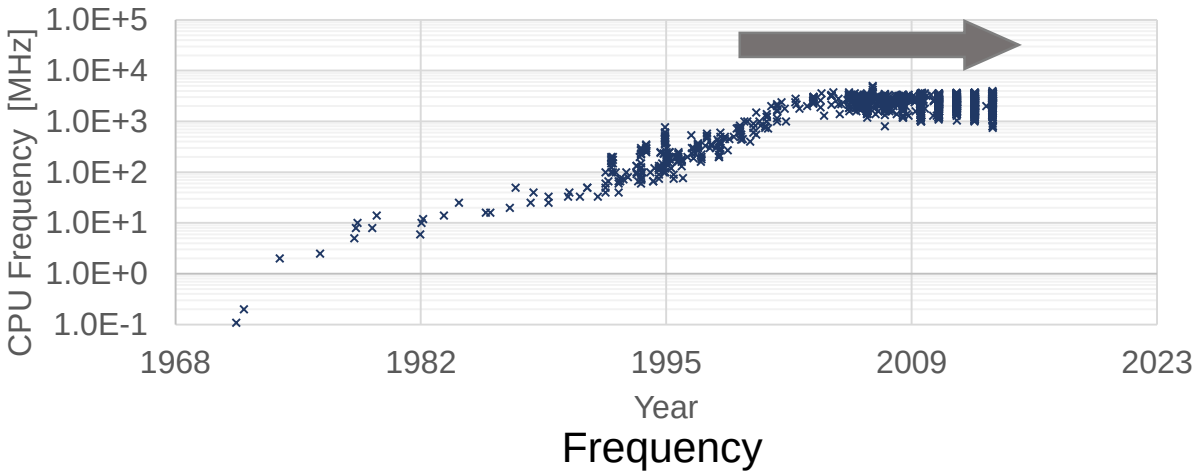
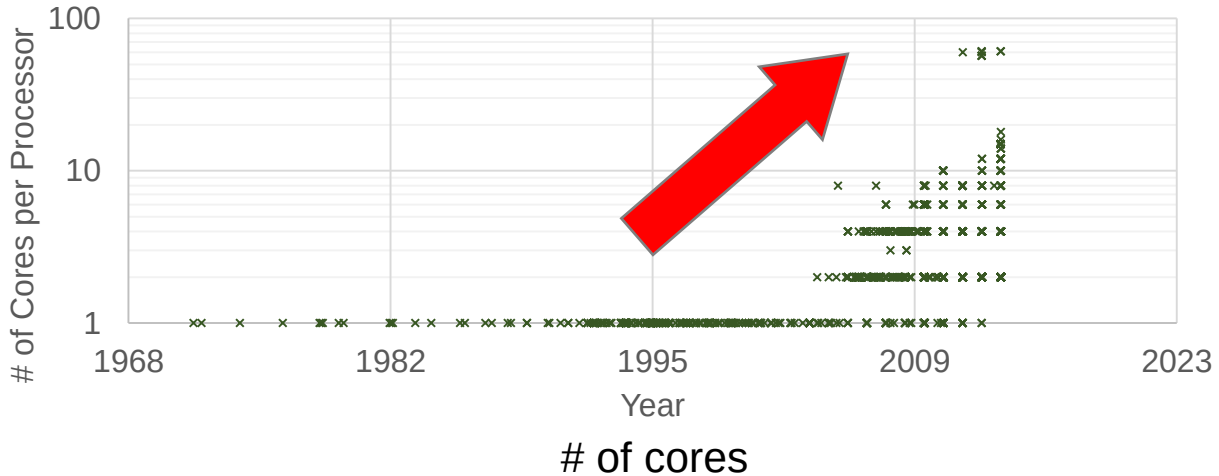
Demands for Lightweight Threads



Frequency

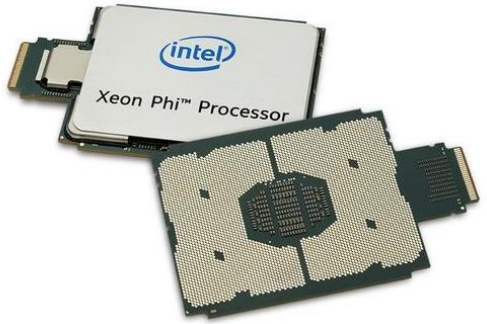


# of cores

CPU DB (http://cpudb.stanford.edu/)

- Increase of cores in a processor.
- Finer-grained parallelism is important to exploit modern CPUs.
  - ➡ Lightweight threads are demanded.

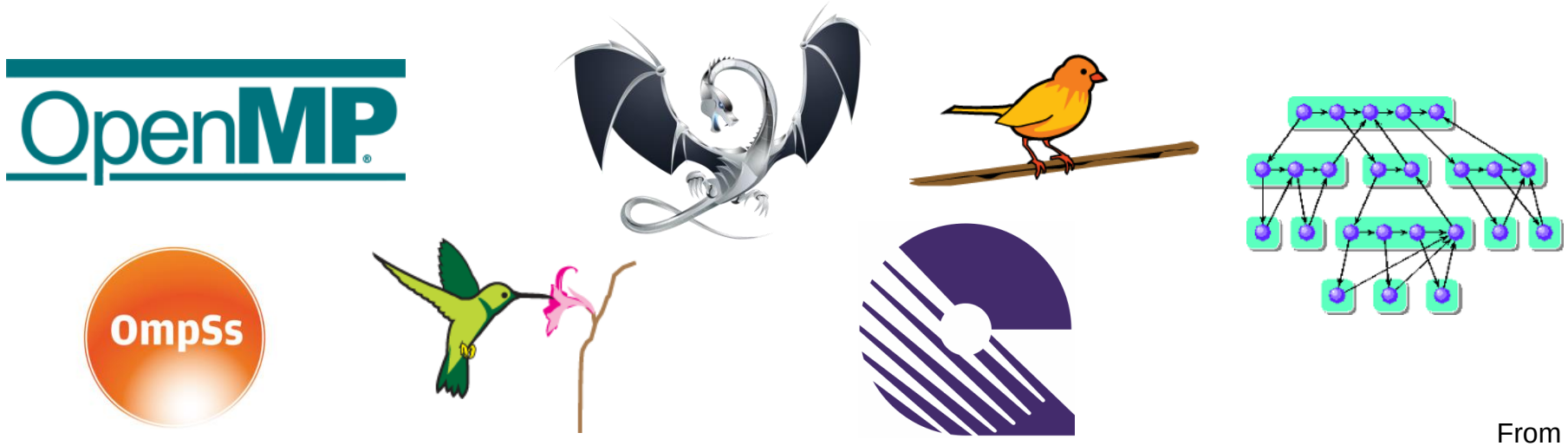
ARM ThunderX2 up to 32 cores, 128 HWTs (https://www.servethehome.com/cavium-thunderx2-review-benchmarks-real-arm-server-option/)



Intel Xeon Phi (Knights Landing) 72 cores, 288 HWTs (https://software.intel.com/en-us/articles/what-disclosures-has-intel-made-about-knights-landing)

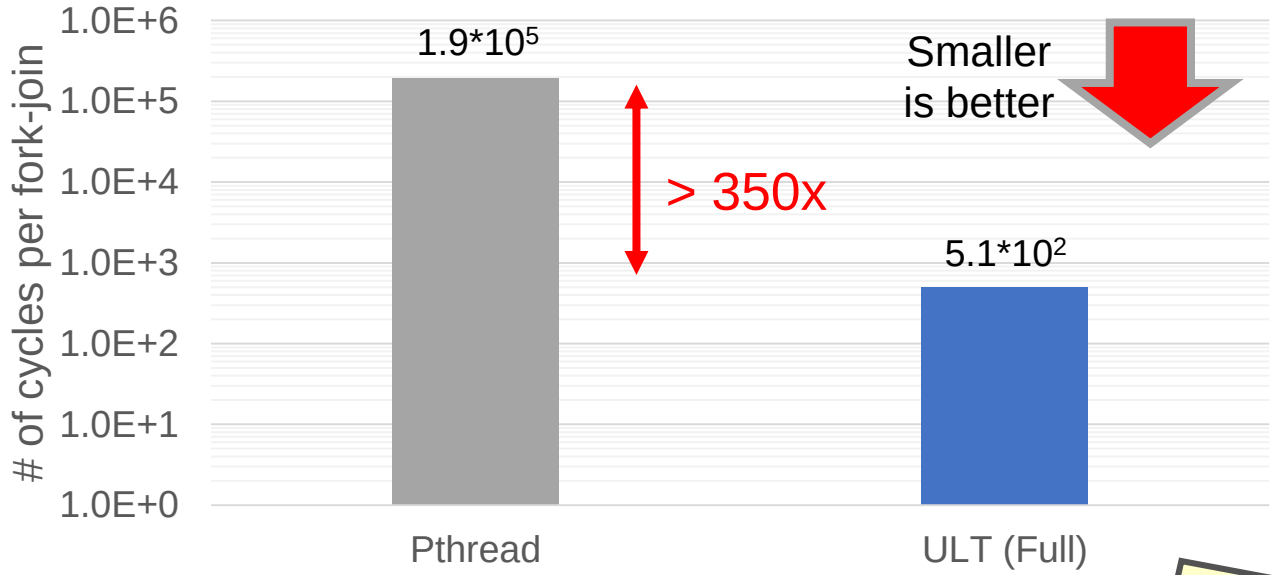
User-Level Threads

- Numerous parallel systems adopt user-level threads (ULTs)
  - Sometimes more than 100x faster than OS-level threads (=kernel threads, e.g., Pthreads)
  - Adopted as lightweight parallel units.
    - Cilk, Intel TBB, CilkPlus, OmpSs (=Nanos), Qthreads, Intel/LLVM OpenMP, Charm++ (=Converse), Filaments, MassiveThreads, Argobots and many



From each official webpage

OS-Level Threads vs. User-Level Threads



- ULTs are 350x faster than Pthreads

➡ We can create more ULTs.

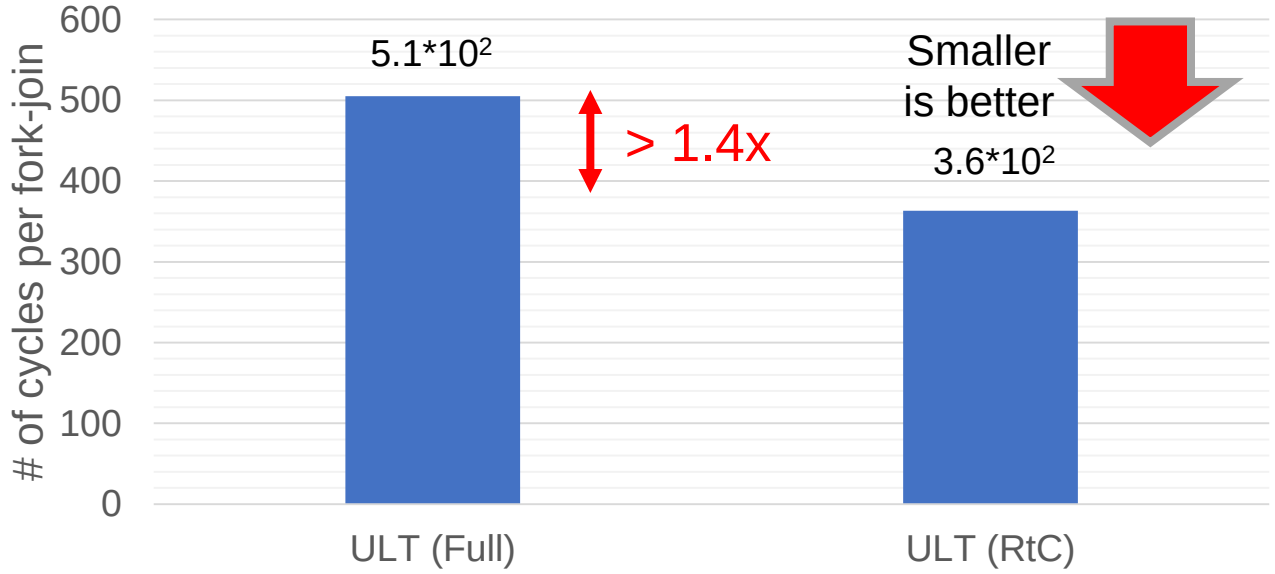
  - Dynamic load balancing (e.g., irregular parallelism)
  - Latency hiding (I/O & network) (e.g., latency-intensive applications)

We used **Argobots**:

- http://www.argobots.org/
- https://github.com/pmodels/argobots

Full = LC, repeat creating 256 threads & joining all of them; no suspension. / pthread: 500 iterations & 10 warm-ups / Full, RtC: 5000 iterations & 100 warm-ups Average of 10 times execution / Intel Xeon Phi 7210 (KNL) 1 core / 1.3GHz (turbo-boost: off) / Compiler: icc 17.2.174 / Stack size : 16KB / Error < 5% / Red Hat 4.8.5-16 / Huge page is enabled.

Two Opposite ULT Techniques



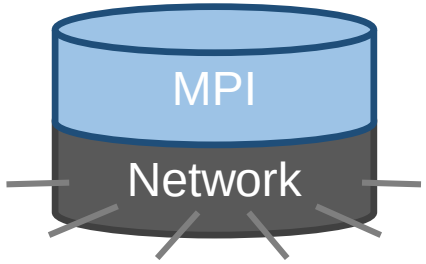
1. Fully-fledged thread (**Full**): fully capable ULTs (i.e., suspendable)
   - **Full** has larger overheads.
     - Adopted by Cilk, CilkPlus, Nanos, Qthreads, MassiveThreads, Argobots, …
2. Run-to-completion thread (**RtC**): ultimately lightweight ULTs
   - **RtC** cannot suspend.
     - Adopted by Filaments, Qthreads, Intel TBB, Argobots, …

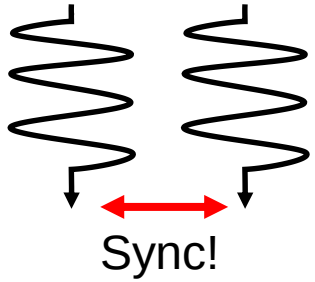
Suspension: Use Cases

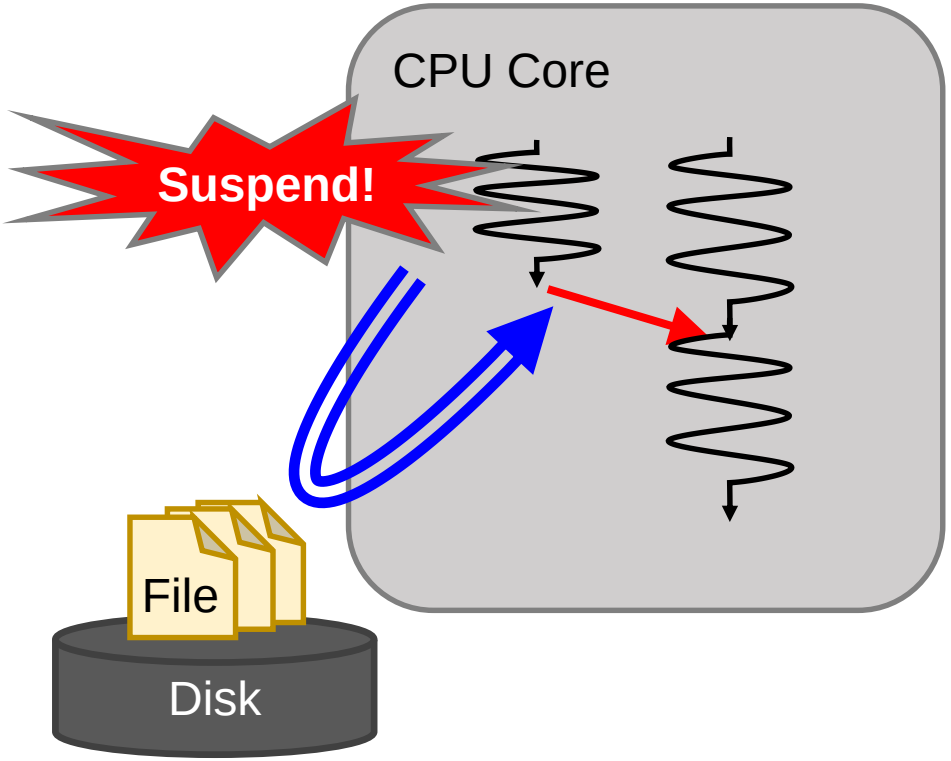
- Suspension: save the thread context, and switch to another thread (similar to `pthread_yield()`)

Full can while **RtC** cannot.

- Suspension is used to efficiently utilize compute resources.
  1. Waiting for a lock (mutex, critical section).
  2. Waiting for I/O or communication.
  3. Waiting for completion of other threads



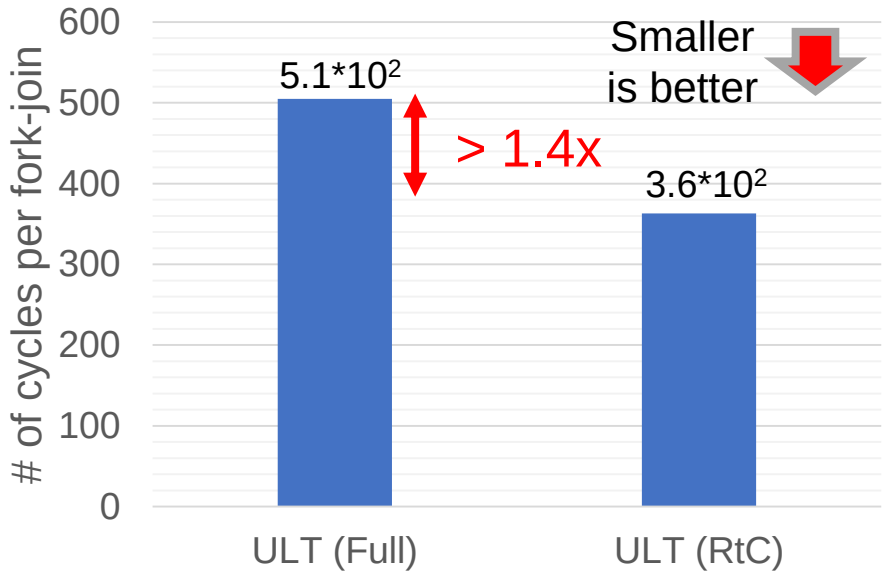




Costs of Suspension Capability

- If a ULT never suspends,
  RtC is faster than **Full**.
  - **Full** has additional threading overheads on fork/join to prepare context switching.

Describe later.



- Suspension demand is application-dependent.
- Case: very few ULTs suspend (e.g., low resource contentions)

Between **Full** and **RtC**: Dynamic Promotion

- Our work investigates a ULT which is
  - as fast as **RtC** if it does not suspend, but
  - able to suspend as well as **Full**

- Key idea: dynamic promotion from **RtC** to **Full**.
  - All of them are applicable to building a threading library.
- Our contributions:
  - In-depth analysis of full spectrum of user-level threading techniques.
  - Two new techniques that do not exist in a past literature.

Most previous work evaluated whole packages, not the individual methods.

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Quick Overview

	Change stack?	# of context switches (nonsuspension)	Performance (nonsuspension)	Constraints	Performance (suspension)
Full	Yes (Eager)	2	Slow	---	Fast
LSA	Yes (Lazy)	2		---	
RoC	Yes (Lazy)	1		-	
SS	Yes (Lazy)	0		Scheduler must be stateless.	
SC	No	0		Scheduler must be stateless. Stack size is shared.	Slow
					(Cannot Suspend)

New

New

TRADE-OFF

Faster!

Stricter constraints!

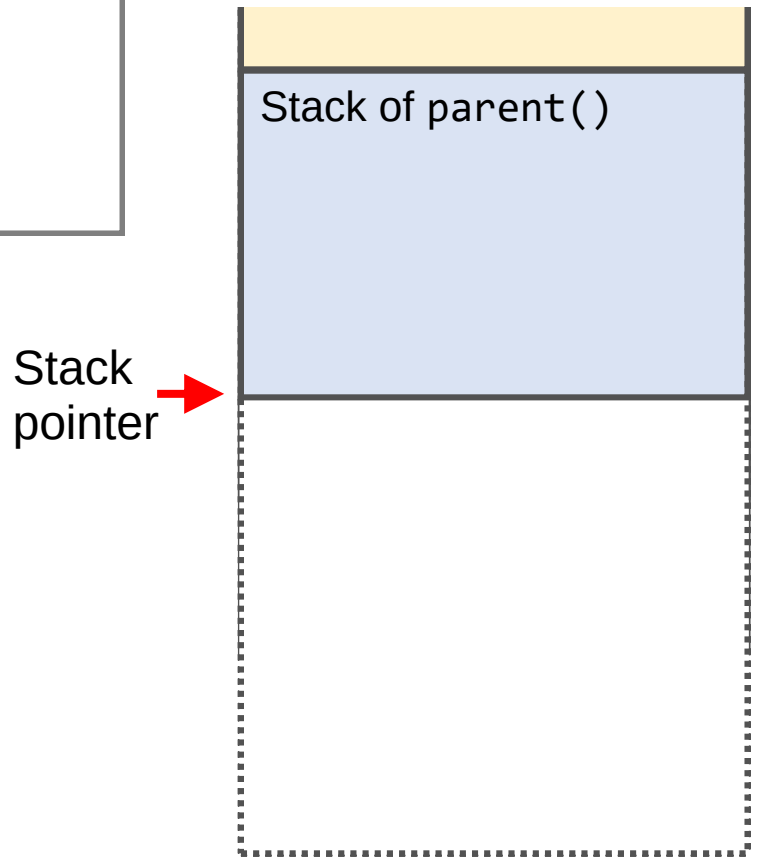
https://www.utep.edu/extendeduniversity/utepconnect/blog/march-2017/4-ways-to-differentiate-a-good-source-from-a-bad-source.html

Flow of Function Call

```
void parent() {
  ...
  child();
  ...
}
```

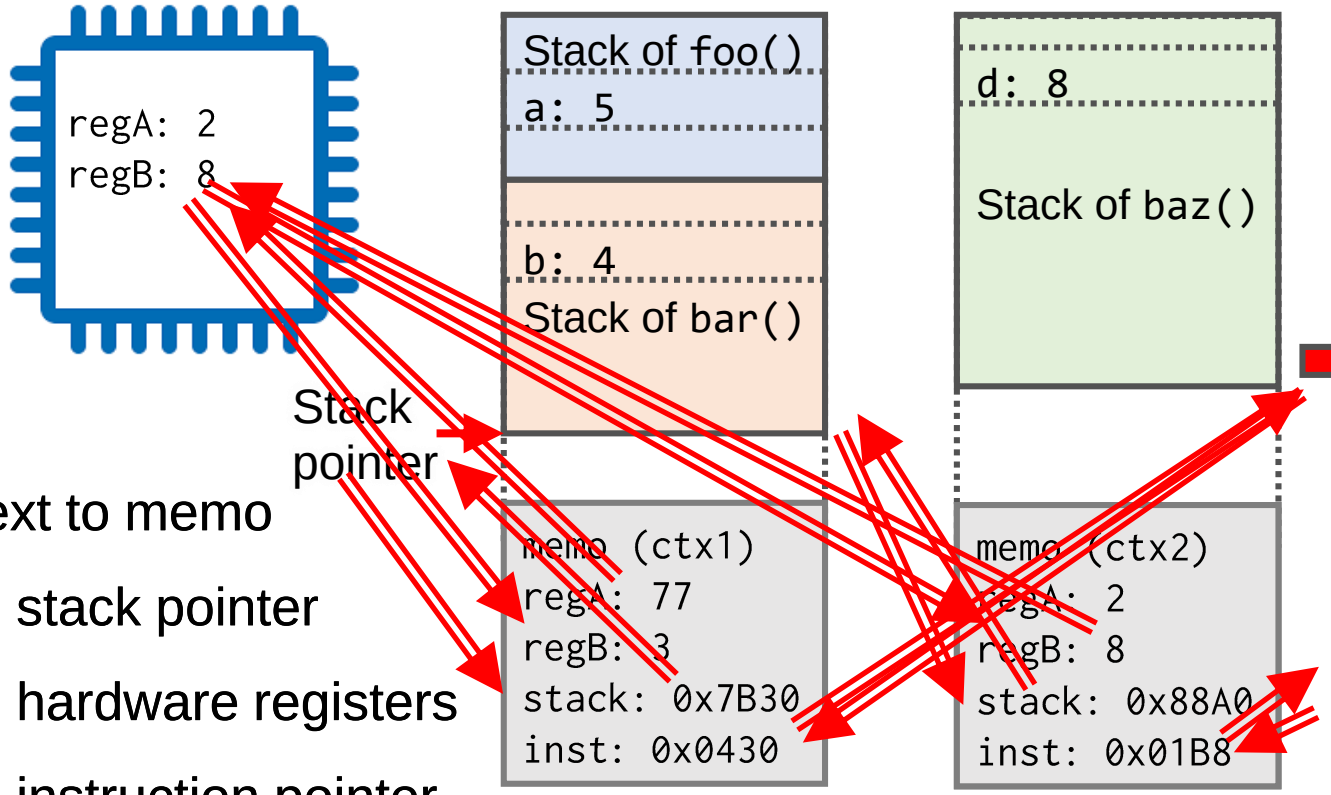
```
void child() {
  [push registers.]
  [...];
  [pop registers.]
}
```

1. `P()`: call to `child()`
2. `C()`: push registers
3. `C()`: run a body of a function
4. `C()`: pop registers
5. `C()`: return to `parent()`



(Naïve) Function Context: Stack & Registers

- Function context = execution state of a function.
- Composed of register values and a function stack.

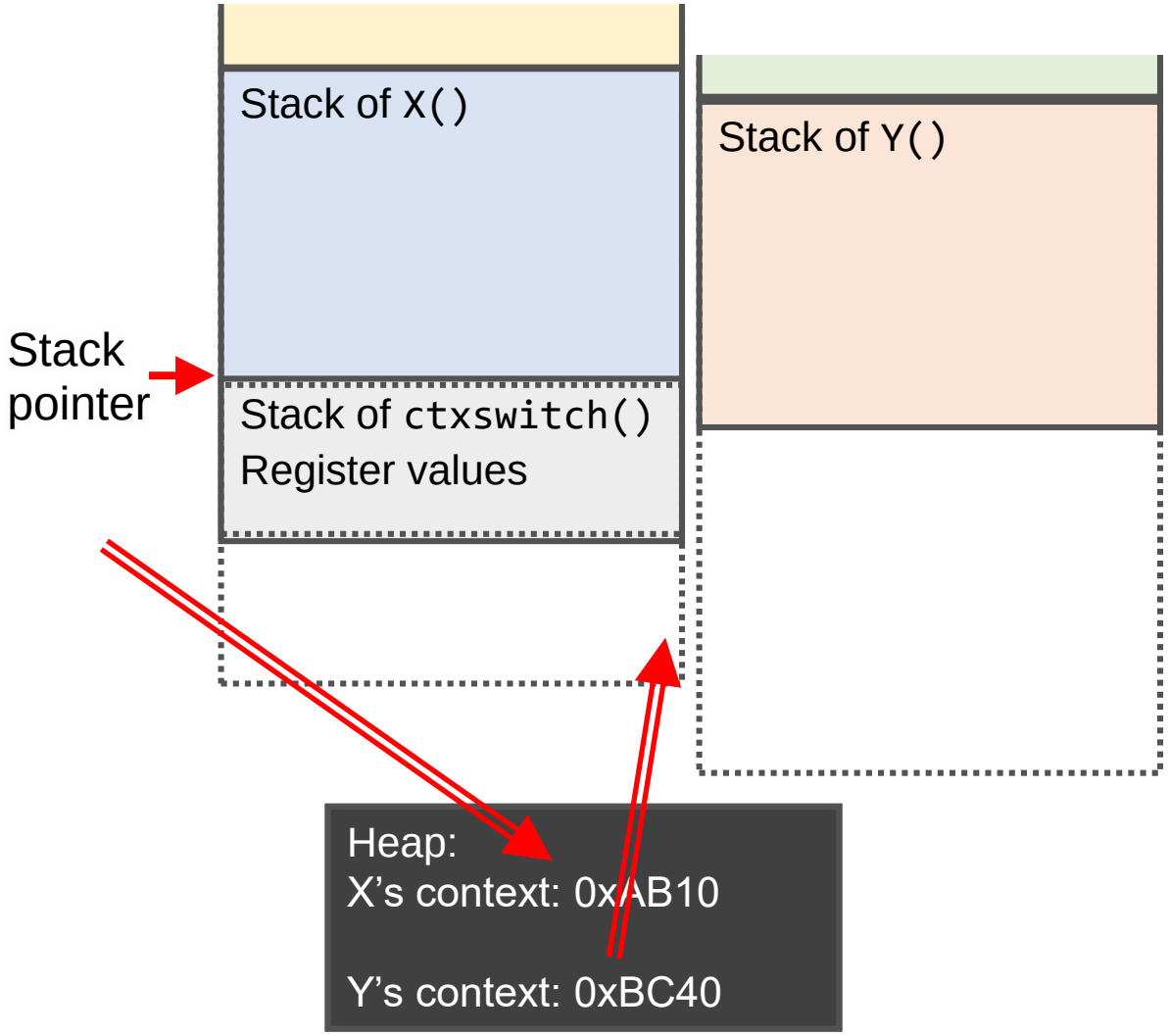



```
void foo() {
  int a = 5; // in stack
  bar();
  [...];
}
void bar() {
  int b = 4; // in stack
  int c = 3; // in regB
  context_switch(&ctx2);
  [...];
}
void baz() {
  int d = 8; // in stack
  int e = 2; // in regA
  context_switch(&ctx1);
  context_switch(&ctx1);
  [...];
}
```

1. Write context to memo
2. Update the stack pointer
3. Update the hardware registers
4. Update the instruction pointer

User-level Context Switch

- Switch from X() to Y()
  1. X(): call ctxswitch()
  2. X(): push registers
  3. X(): save a X()'s stack pointer
  4. X(): set a Y()'s pointer
  5. Y(): pop registers
  6. Y(): jump to a return address

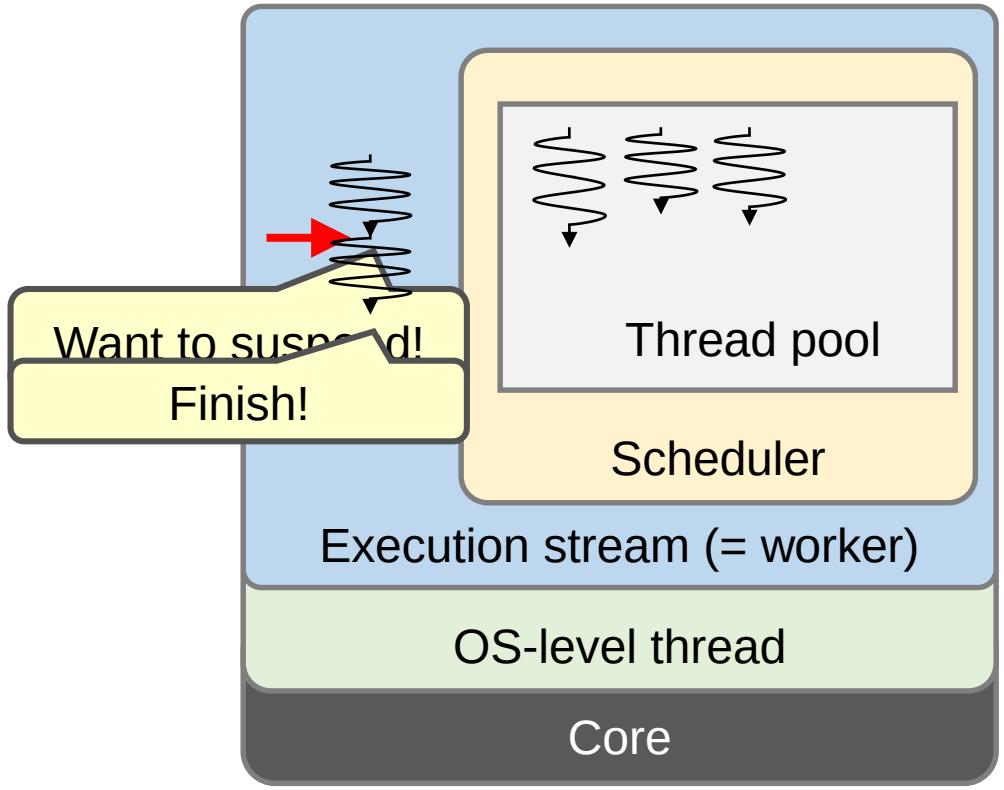


Parent-first

Execution Model of ULTs

- An execution stream (= a worker) is bound to a core.
- A scheduler is running on an execution stream.
  - The scheduler has a loop to execute ULT in the pools.

```
void scheduler() {
  while (1) {
    [get ULT from pool(s)]
    resume ULT;
    if (!ULT.finished)
      [add ULT to a pool]
  }
}
```

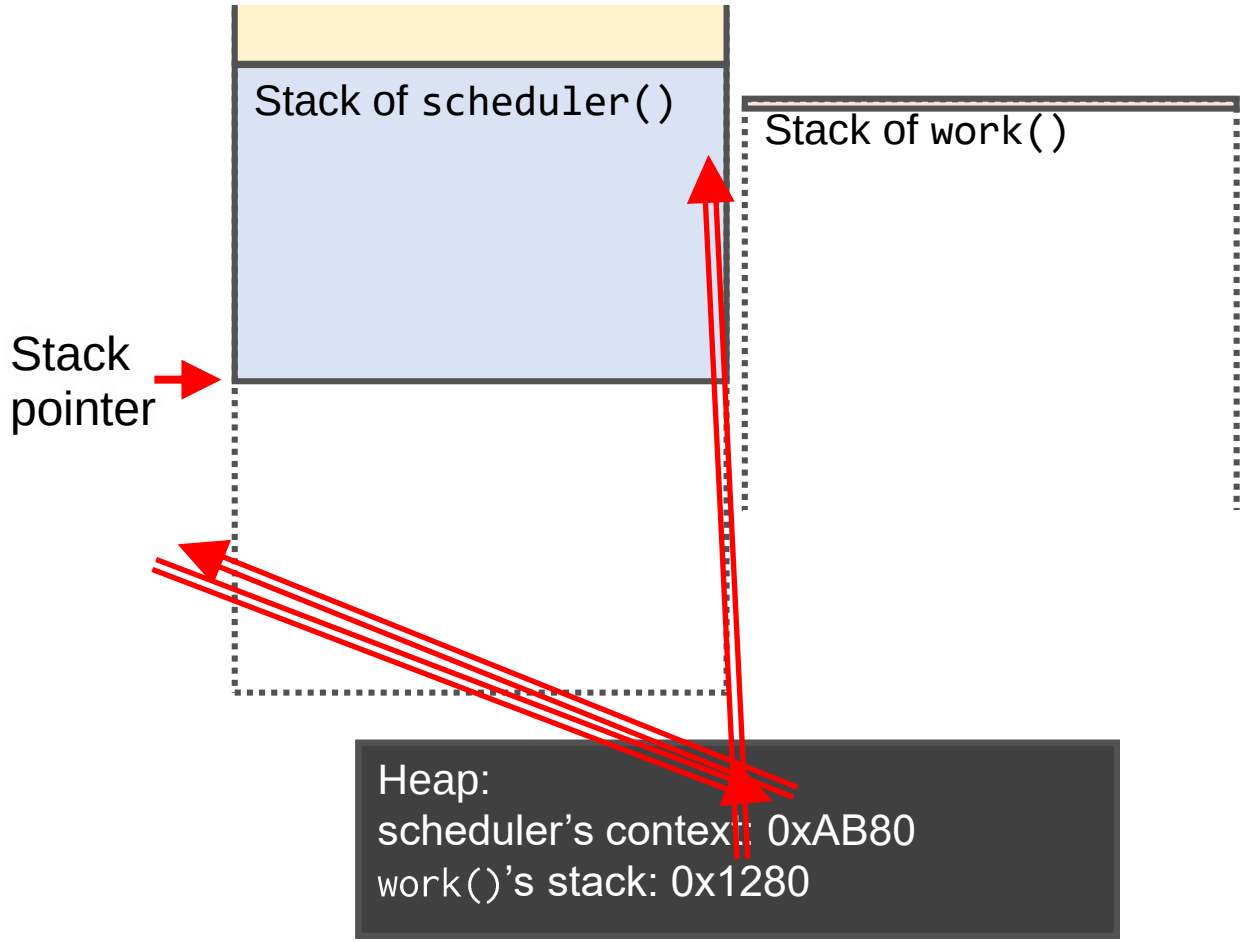


Full : Nonsuspension Case

"call"
1. `S()`: call `ctxswitch()`
2. `S()`: push registers
3. `S()`: save a `scheduler()`'s stack pointer
4. `S()`: set a `work()`'s stack pointer
5. `S()`: call `work()`

6. `T()`: [… run a function body …]

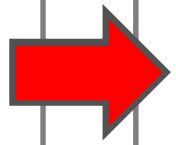
"return"
7. `T()`: restore an `scheduler()`'s stack pointer
8. `S()`: pop registers
9. `S()`: jump to a return address



RtC : Nonsuspension Case

- Ultimately, **RtC** is a function pointer and its argument.
  - Schedulers can just call it

```
void scheduler() {
  while (1) {
    [take ULT from pool(s)]
    resume ULT;
    if (!ULT.finished)
      [add ULT to a pool]
  }
}
```



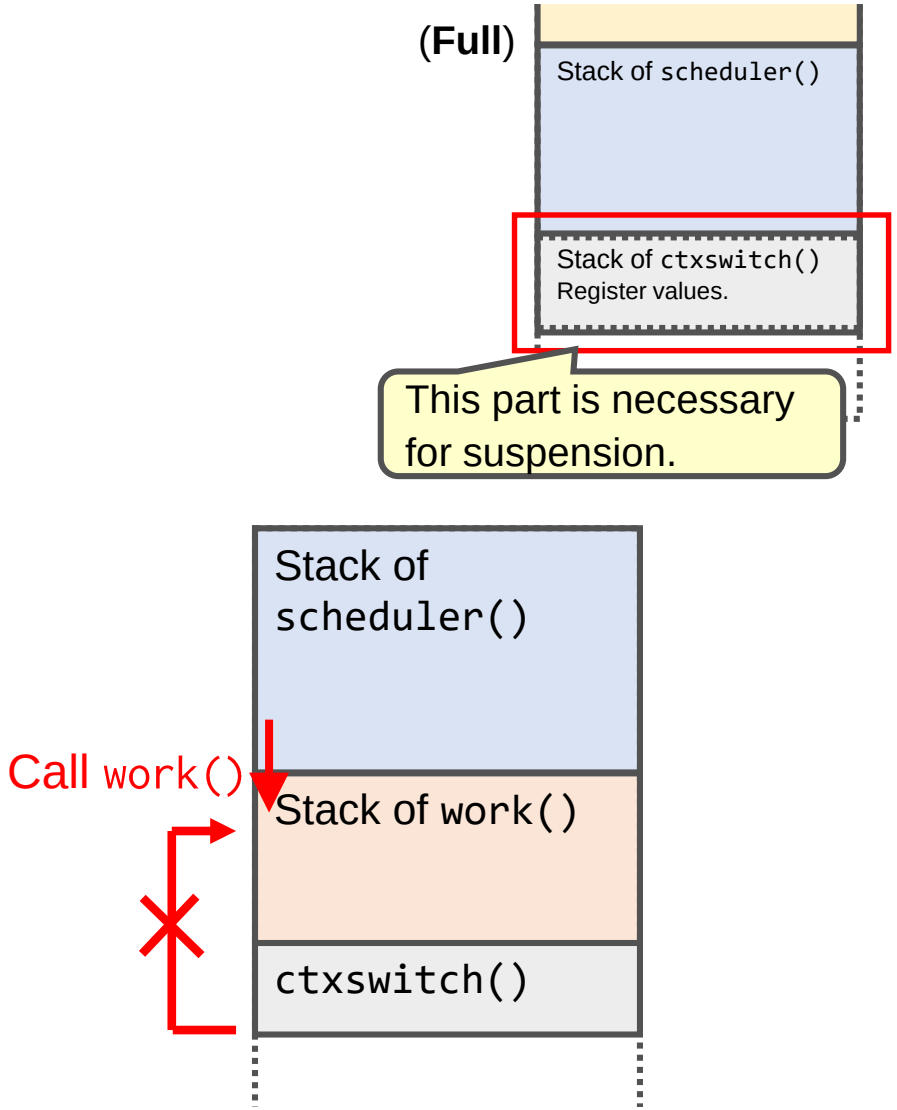
```
void scheduler() {
  while (1) {
    [take ULT from pool(s)]
    call ULT.work(ULT.arg);
  }
}
```

RtC never suspends.

RtC Can't Suspend

- Because registers, a stack pointer, and an instruction pointer are unsaved, we cannot resume `scheduler()`.

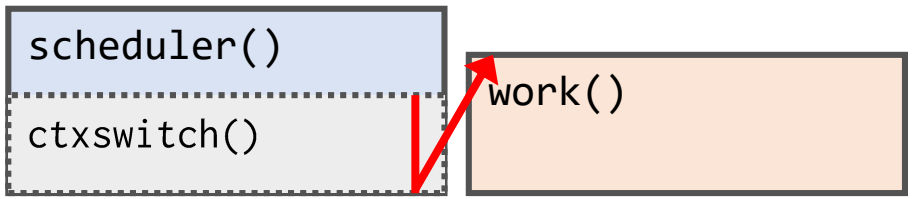
```
void scheduler() {
  while (1) {
    [take ULT from pool(s)]
    call work(arg);
  }
}
```



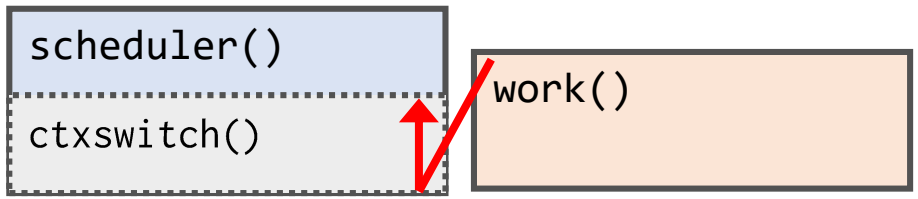
When ULTs do not suspend

[Summary] Costs: **Full** vs. **RtC**

- **RtC** : 1 function call + scheduling
  - Scheduling = thread pool operations + descriptor management … etc.
- **Full :** 1 function call + scheduling
  + 2 user-level context switches + stack management
    1. When a ULT starts
    2. When a ULT finishes.



1st context switch (invoke a ULT)



2nd context switch (resume scheduler)

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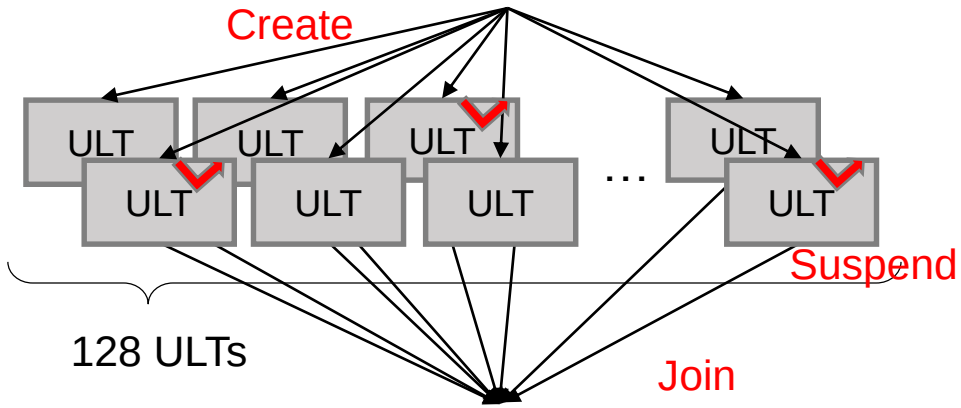
Microbenchmark: fork-join+suspend

- Analysis is based on a fork-join + yield benchmark:
  - Create and join 128 threads
    - S % of 128 ULTs suspend once
    - We run it on Intel Xeon E5-2699 v3.

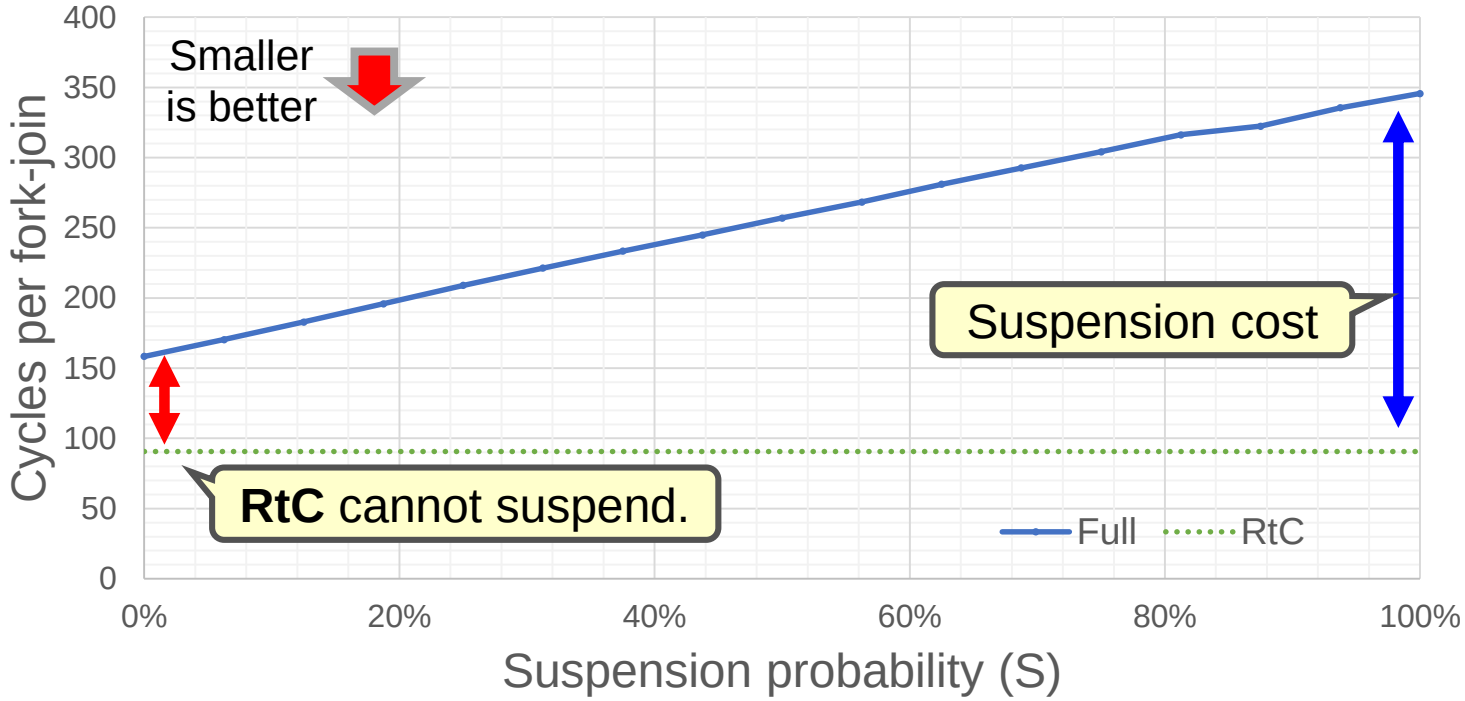



```
void body(void* arg) {
  if ((intptr_t)arg == 1)
    suspend();
}
```

```
HANDLE ts[128]
for (int i = 0; i < 128; i++)
  create(body, suspend_flags[i], &ts[i]);
for (int i = 0; i < 128; i++)
  join(ts[i]);
```

- Show dynamic promotion techniques from **Full**
  - Focus on the performance when threads do not suspend.

From **Full** to **RtC**

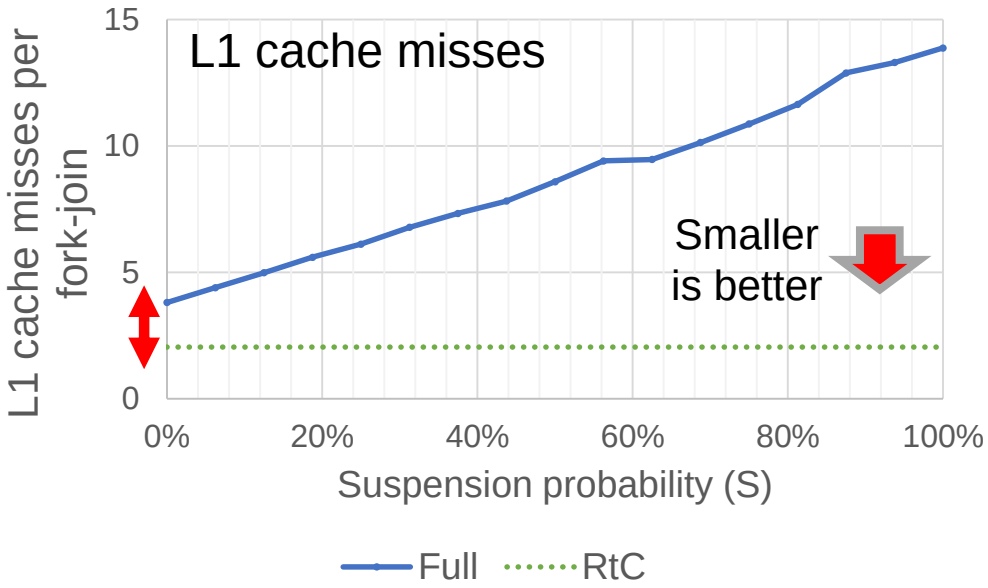


- Suspension probability (=*S*) = $\dfrac{\text{\# of threads that suspend}}{\text{total \# of threads}}$

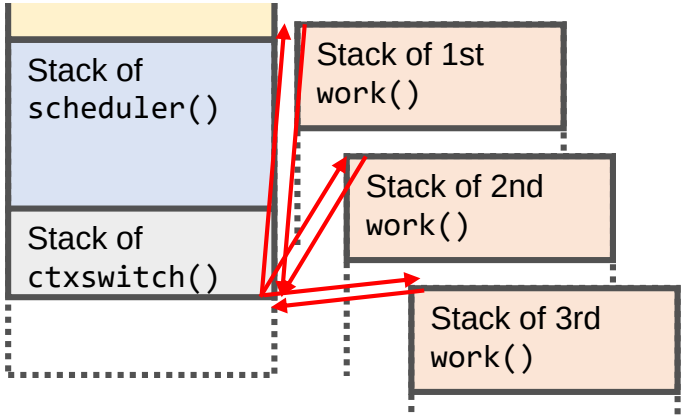
- Narrow the performance gap at S = 0%

Costs of Fully Fledged ULTs (**Full**)

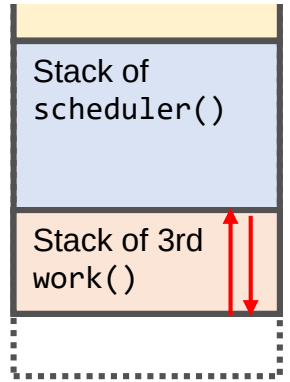
- **Full:** more cache misses because all ULTs use different function stacks.
  - Stacks are allocated when **Full** is created.
- **RtC:** small cache misses because they use the same function stack.
  - The scheduler's stack is reused.



Full:



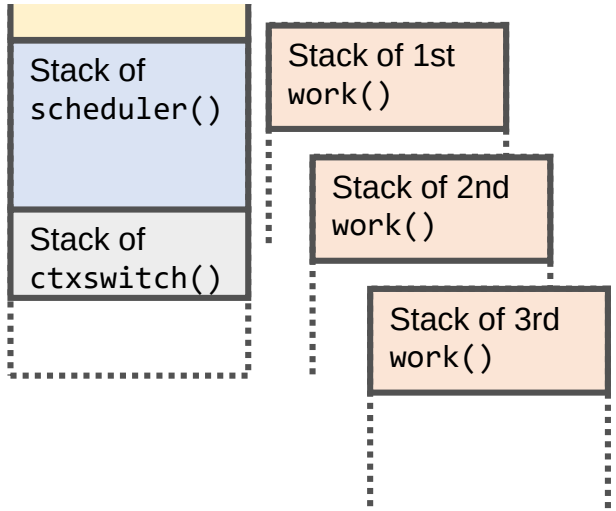
RtC:



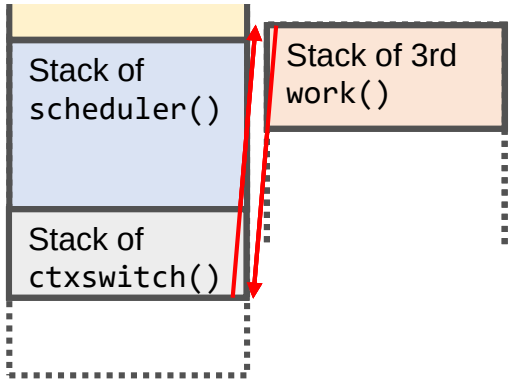
Lazy Stack Allocation (**LSA**)

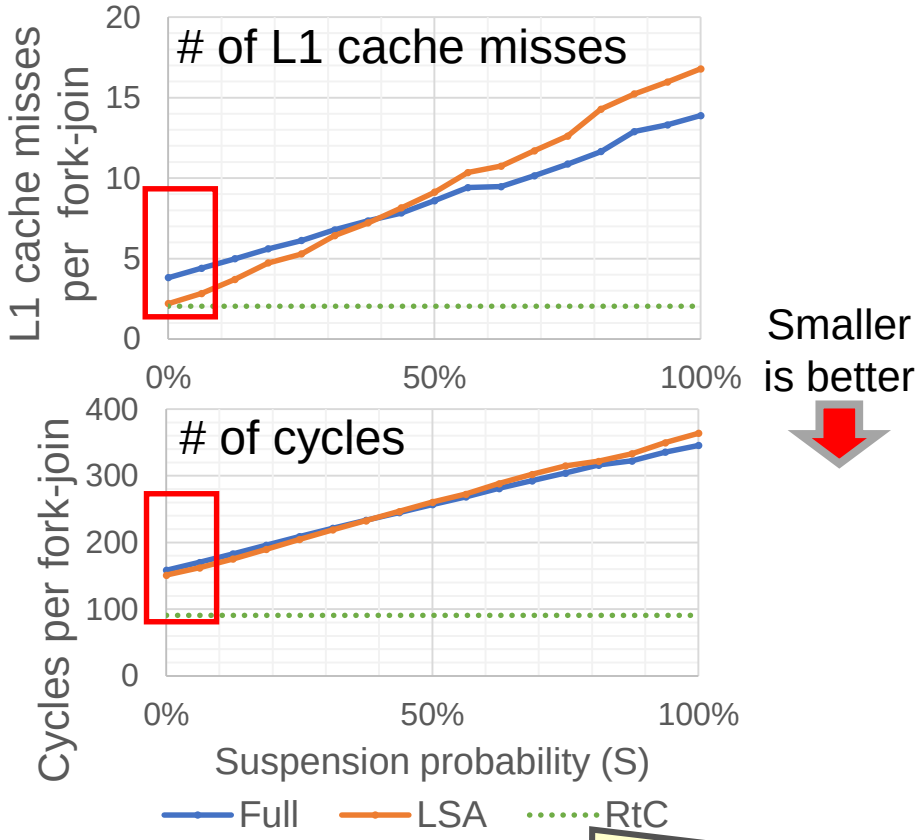
- Lazy stack allocation (**LSA**): allocates stacks when ULTs are invoked, not created.
  - If a ULT did not suspend, the next ULT uses the same stack.

Full:



LSA:



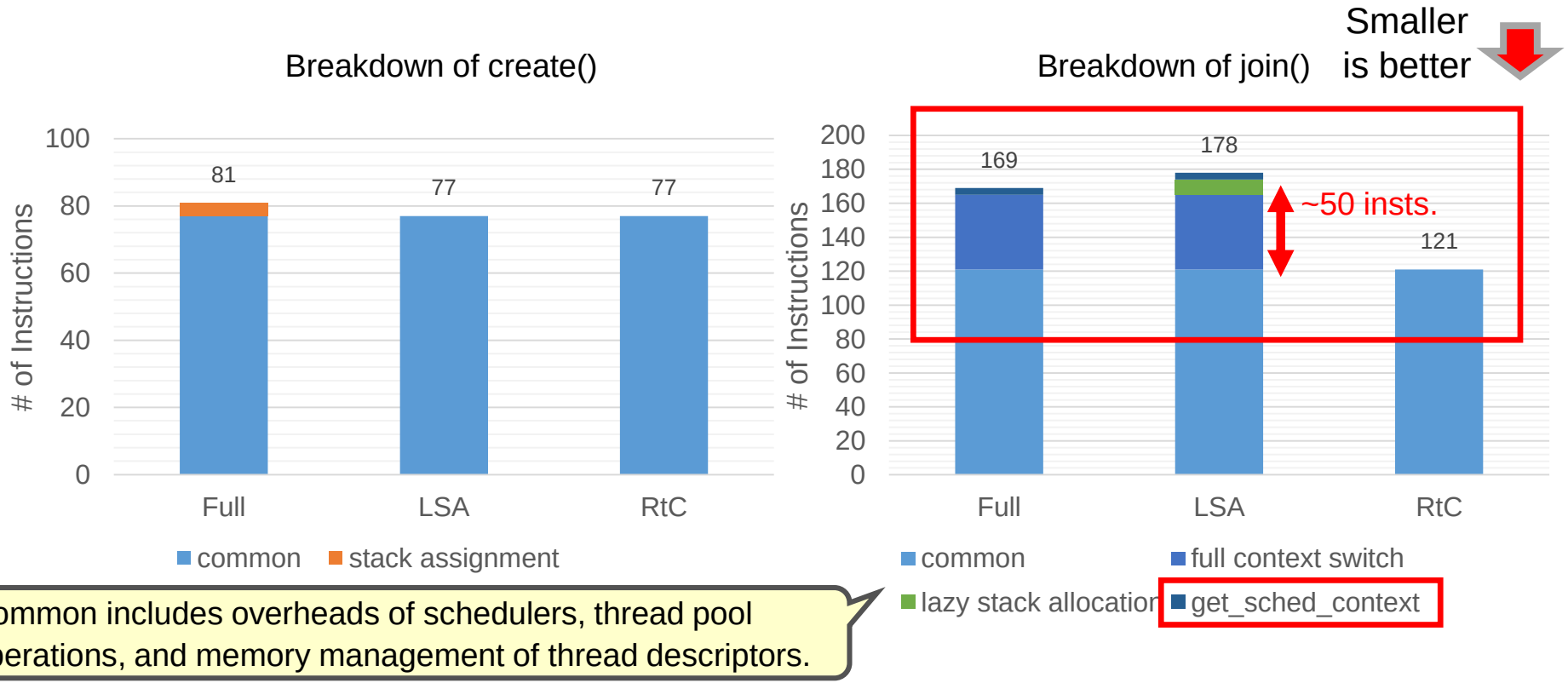


Smaller is better

Full allocates a thread descriptor and stack at once, while **LSA** does separately. It degrades **LSA**'s performance when the suspension probability is high.

Costs of **LSA** : Two Context Switches

- Compared to **RtC**, # of instructions is quite large.
  - Costly part: user-level context switches (=stack and register manipulation)



Common includes overheads of schedulers, thread pool operations, and memory management of thread descriptors.

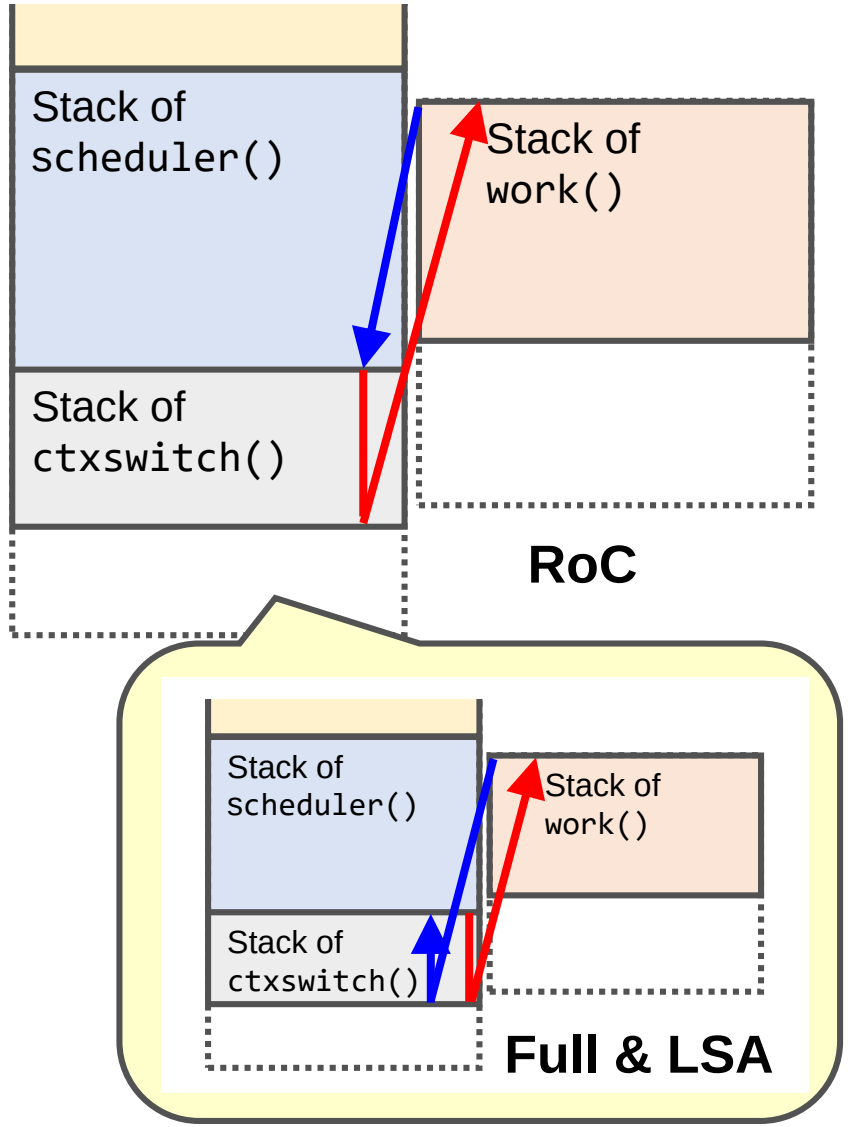
Return-on-Completion (**RoC**)

- The first context switch is necessary to save the scheduler's context.
  - Needed for the future resume.
- The second context switch can be replaced by return if it just jumps to the parent if the ULT never suspends.
  - An assembly-level trick enables it.

(*) In general, a caller cannot be resumed by "return" because user-level context switch does not follow a standard ABI.

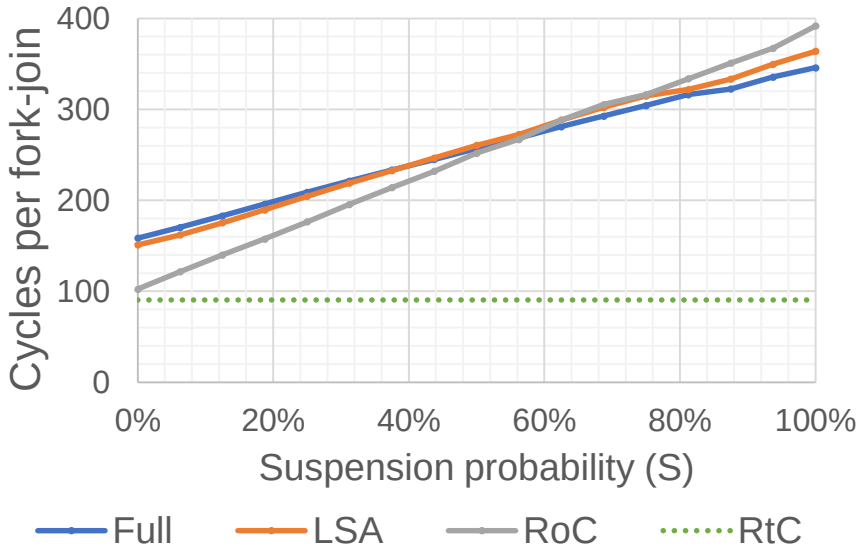
  - If the ULT suspends, `ctxswitch()` is called at the end of `work()`.

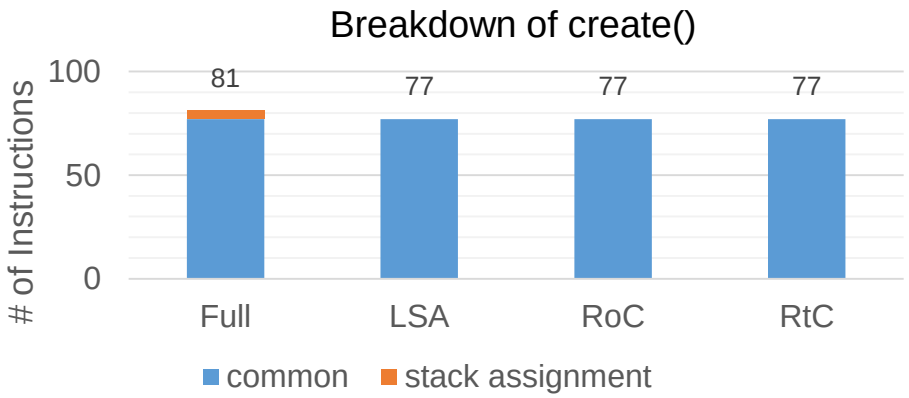
➡ *Return-on-completion* (**RoC**)

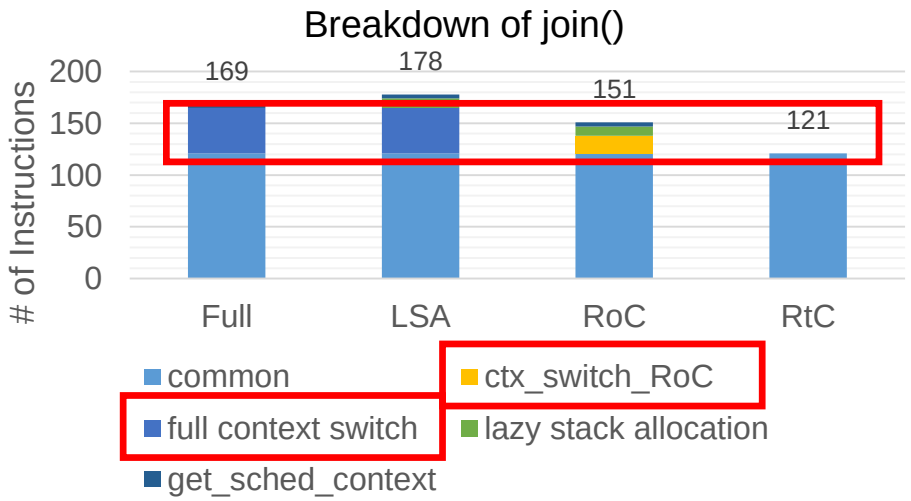


RoC: Performance

- **RoC** successfully reduces # of instructions.
  - Good performance when the suspension probability is low.





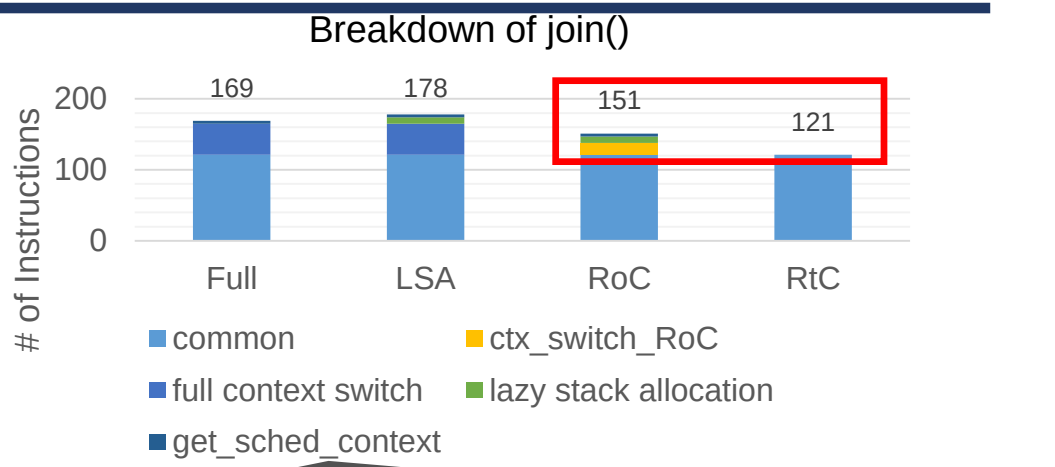


Costs of **RoC** : One Context Switch

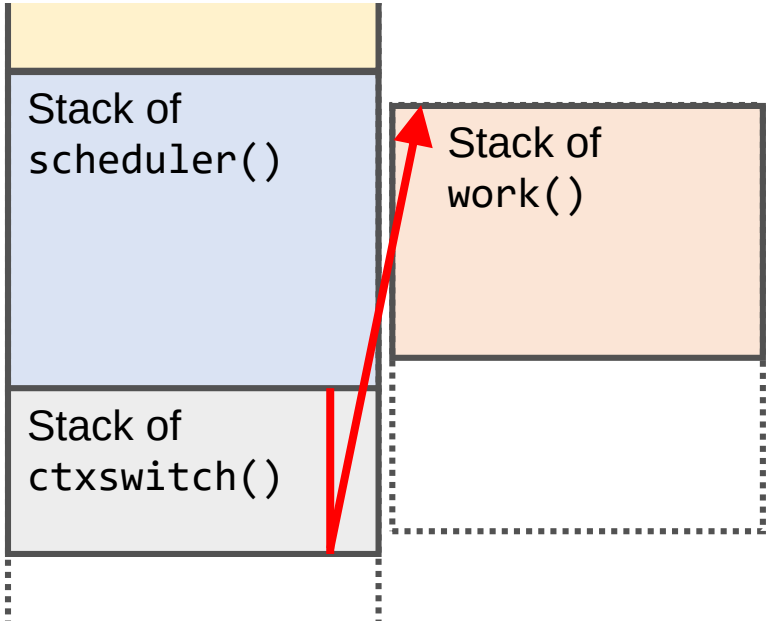
- Compared to **RtC**, # of instructions of **RoC** is still large.
  - Caused by the first user-level context switch and the stack management.
  - They are necessary to resume a parent ULT.

This part:

- What if we can restart a scheduler instead of resuming it?

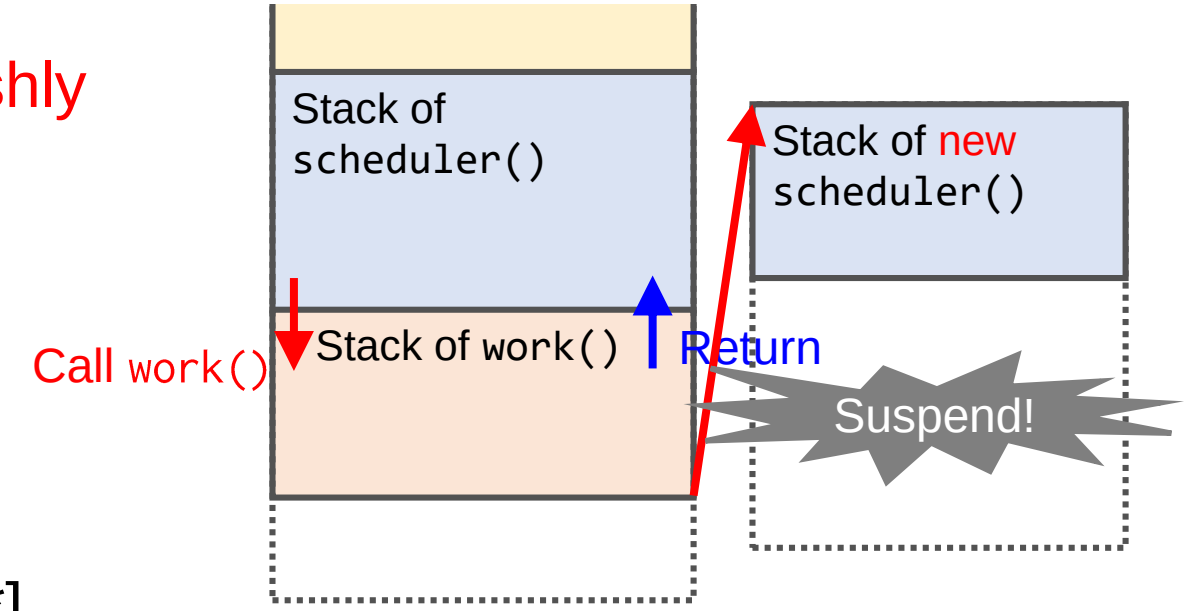


`ctx_switch_RoC` includes one context switch.



Scheduler Creation (**SC**)

- Assume schedulers are running on ULTs.
- If the scheduler is *stateless*, we can freshly start a scheduler on the new ULT.
  - The context of the original scheduler is abandoned.



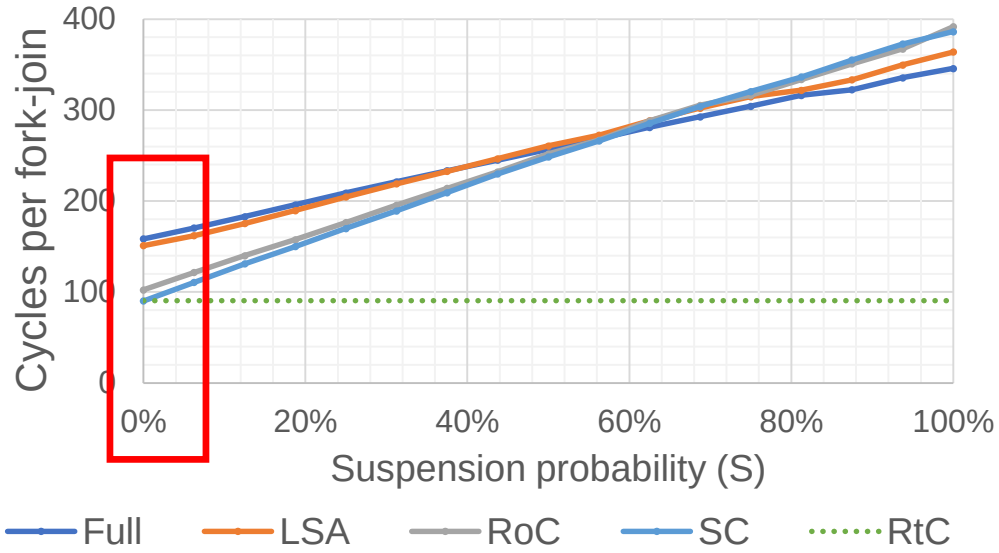
- It has been previously proposed [*] - [***].
- Let's call *scheduler creation* (**SC**).

It has almost the same execution flow of **RtC.**

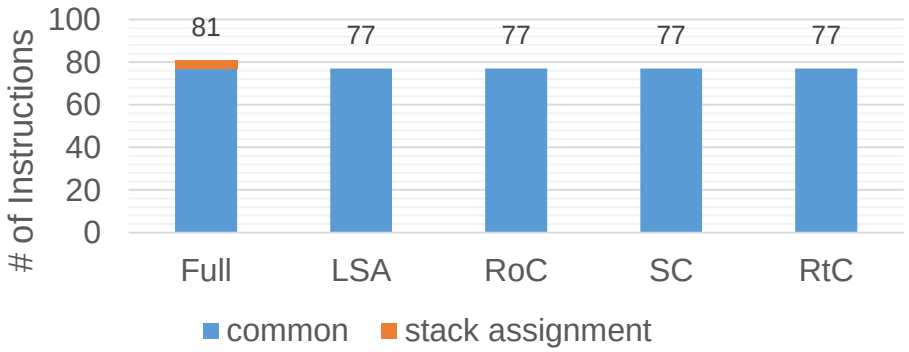
[*] D. L. Eager and J. Jahorjan. Chores: Enhanced run-time support for shared-memory parallel computing. TOCS. 1993
[**] K.-F. Faxén. Wool - A work stealing library. SIGARCH Comput. Archit. News, 2009.
[***] C. S. Zakian, T. A. Zakian, A. Kulkarni, B. Chamith, and R. R. Newton. Concurrent Cilk: Lazy promotion from tasks to threads in C/C++. LCPC '15, 2016

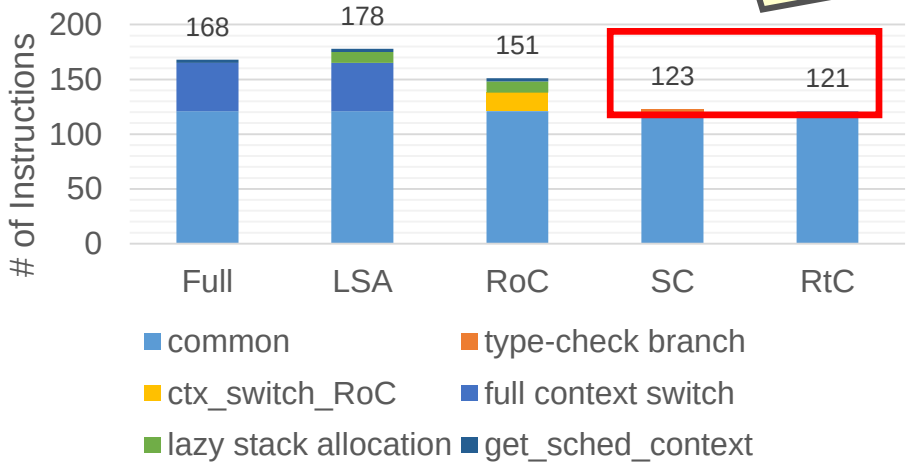
Performance of **SC**

- SC performs as well as RtC when S = 0%.



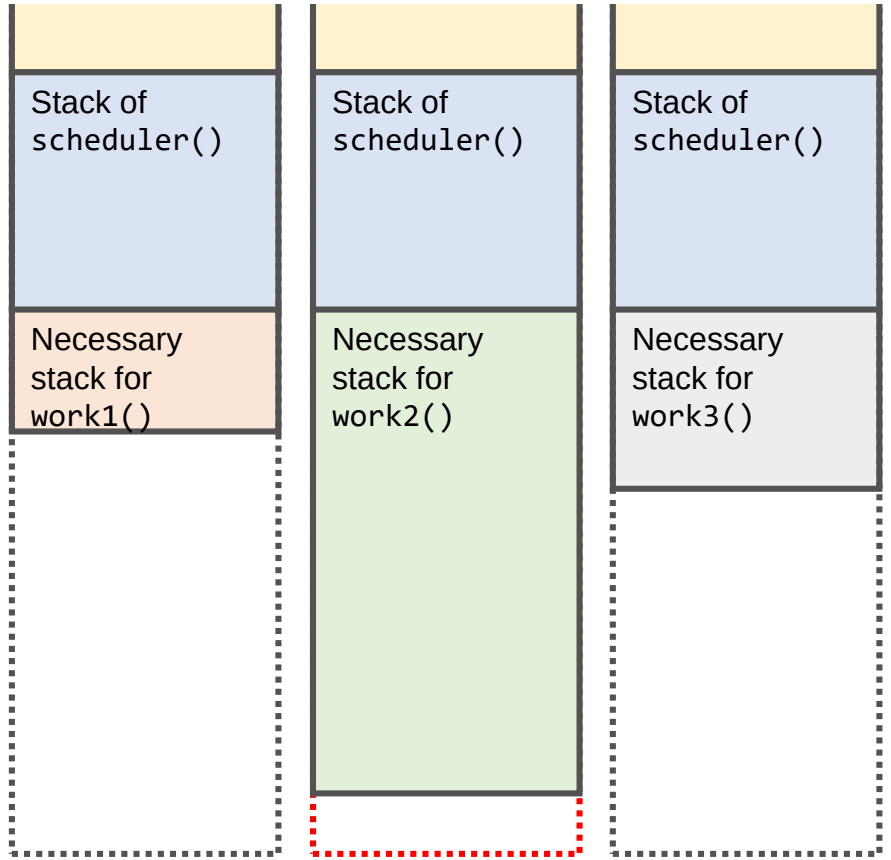
Difference is only 2 instructions!





Constraints of **SC**

1. The scheduler must be stateless.
2. Stack size of schedulers and ULTs must be shared.
   - e.g., an application has multiple types of work each of which requires different stack size.

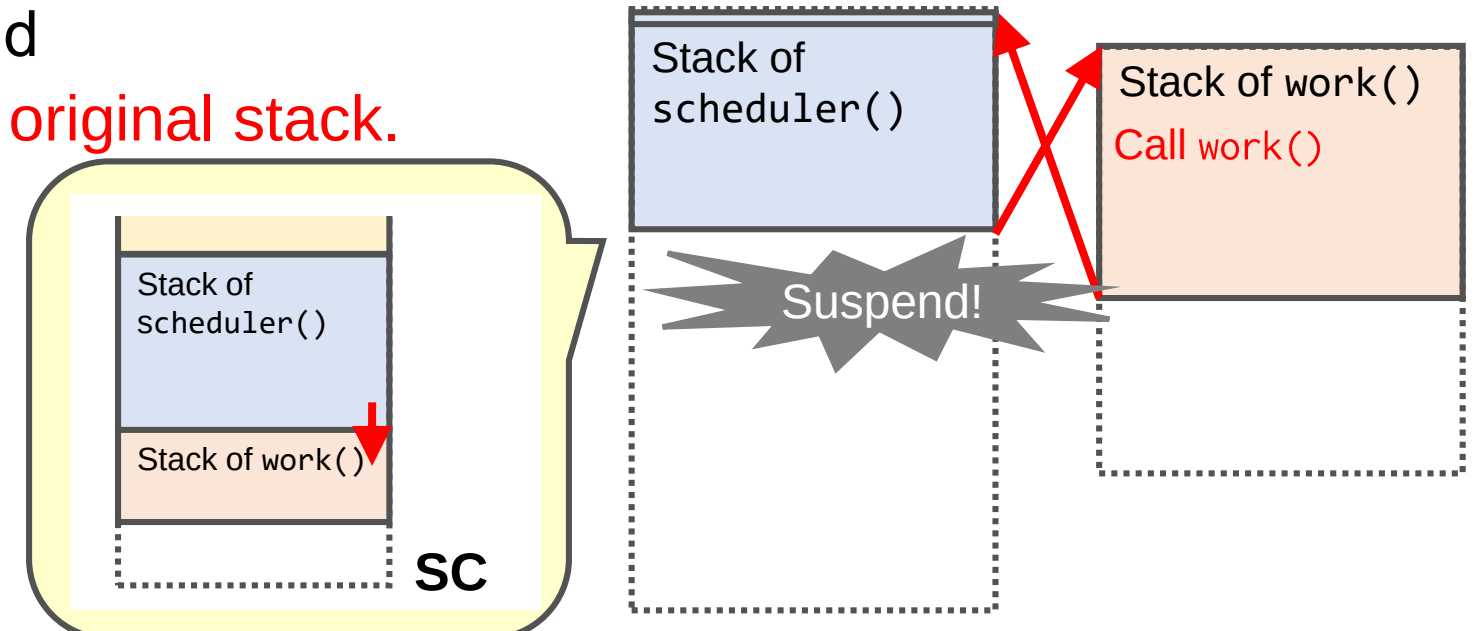


➡ Remove the 2nd constraint by using different stacks.

Individual ULTs cannot specify the size of stacks
➡ Need to use largest size!

Stack Separation (**SS**)

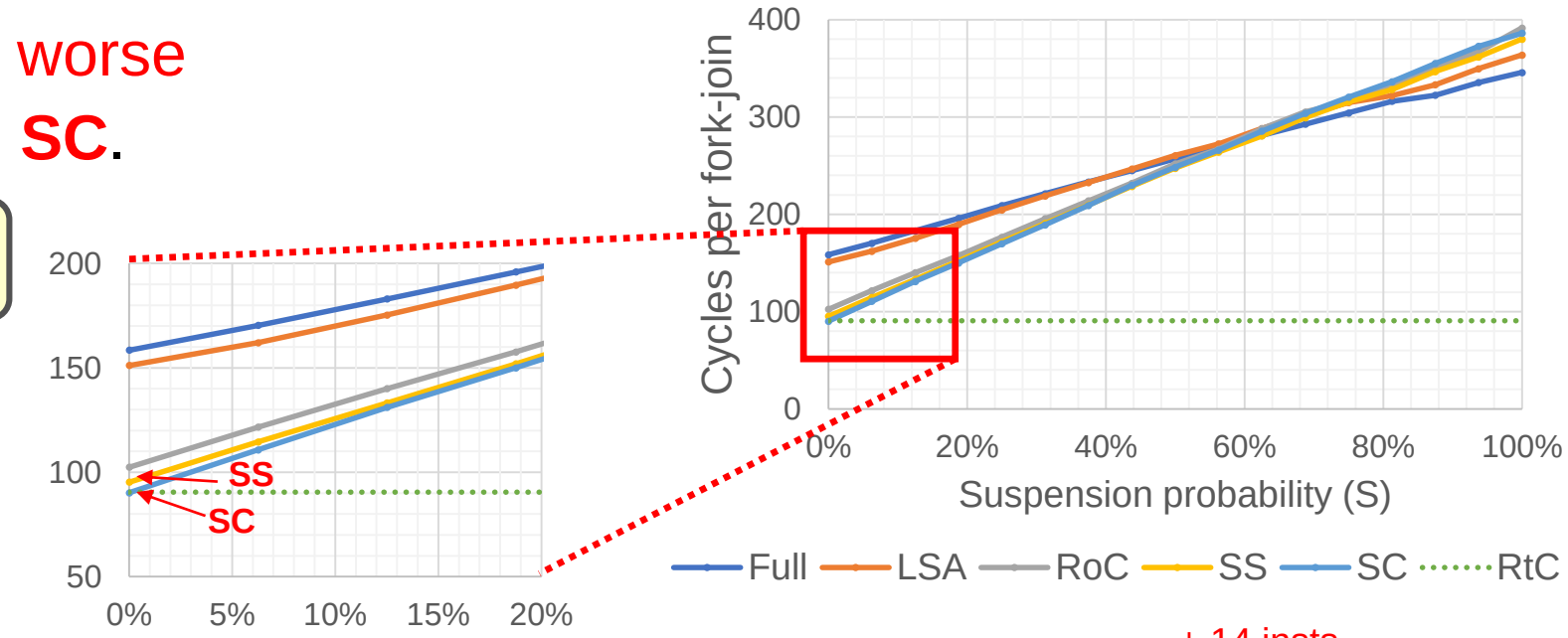
- *Stack separation* (**SS**): it does not save register values of the scheduler, but uses different stacks.
  - Because the context of the parent scheduler is not fully saved, the scheduler must be stateless.
- When `work()` suspends, it renews the `scheduler()`'s stack and calls `scheduler()` over the original stack.

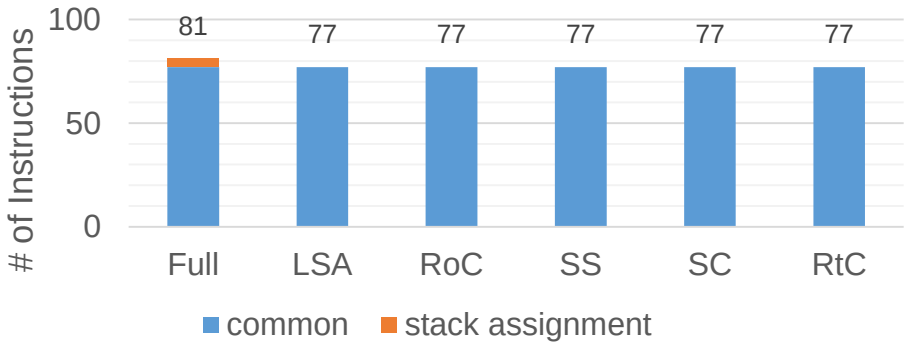


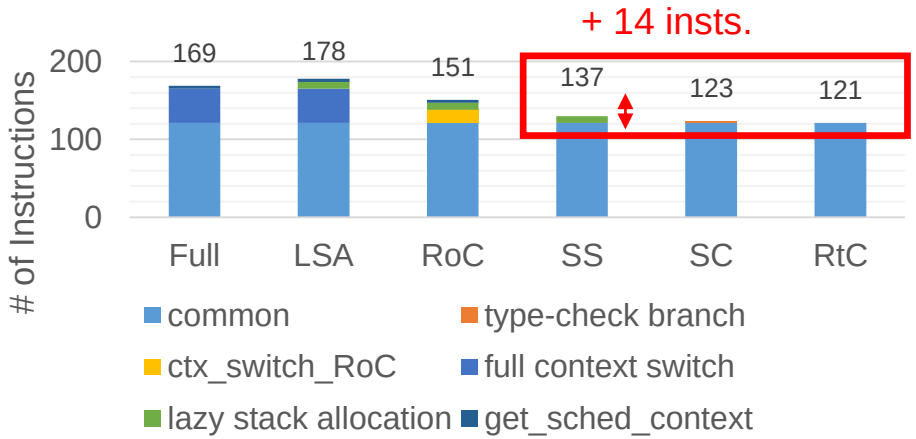
Performance of **SS**

- **SS** shows slightly worse performance than **SC**.

Because of additional instructions!







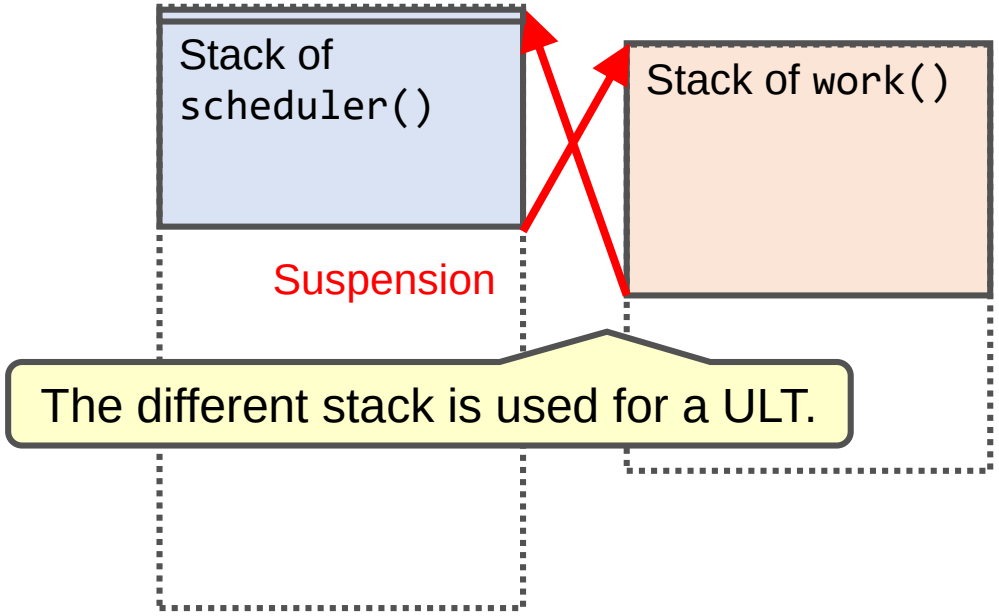
Constraints of **SS**

1. The scheduler (or in general, the parent function) must be stateless.

= 1st constraint of **SC.**

2. ~~Stack size of schedulers and ULTs must be shared.~~

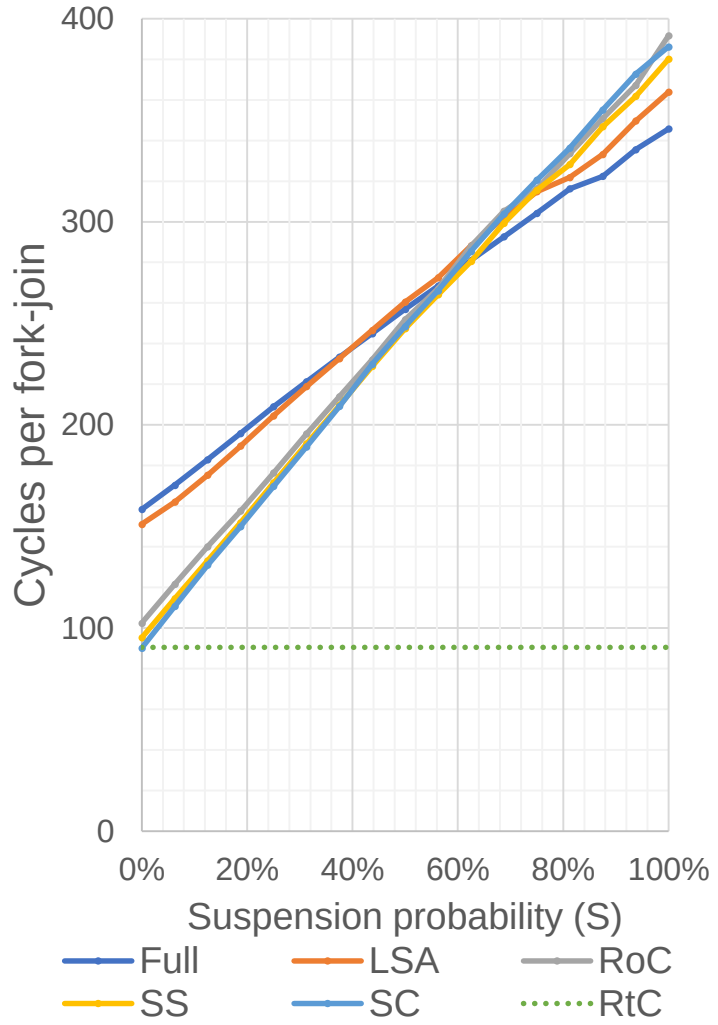
   - Stacks are not shared!



Summary

	S=0% Case (No suspension)			S=100% Case		
	Change Stack?	# of ctx switches	Overhead	Rerun sched.?	Overhead	Constraints
Full	Yes	2	High	No	Low	No
LSA	Yes	2		No		No
RoC	Yes	1		No		No
SS	Yes	0		Yes		*
SC	No	0		Yes	High	**
RtC	No	0	Low	-	-	***

* Schedulers must be stateless.
** Schedulers must be stateless. Stack size of schedulers and ULTs is shared.
*** Threads are unable to yield.



- Typical trade-off relationship.
  - Performance at S=0% and performance at S=100%.
- **SS**, **SC**, and **RtC have** additional constraints.

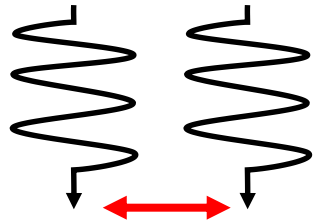
Index

1. Introduction : Lightweight threads
2. Background : How ULTs work
3. Analysis & Proposals
4. Evaluation
5. Conclusions

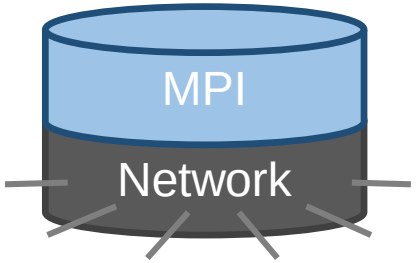
Three Motivating Cases

1. Waiting for mutexes.
   - KMeans: simple machine learning algorithm.
     ULTs access shared arrays with locks.

2. Waiting for completion of other threads
   - ExaFMM: divide-and-conquer O(N) N-Body solver.
     Parent ULTs need to wait for children.

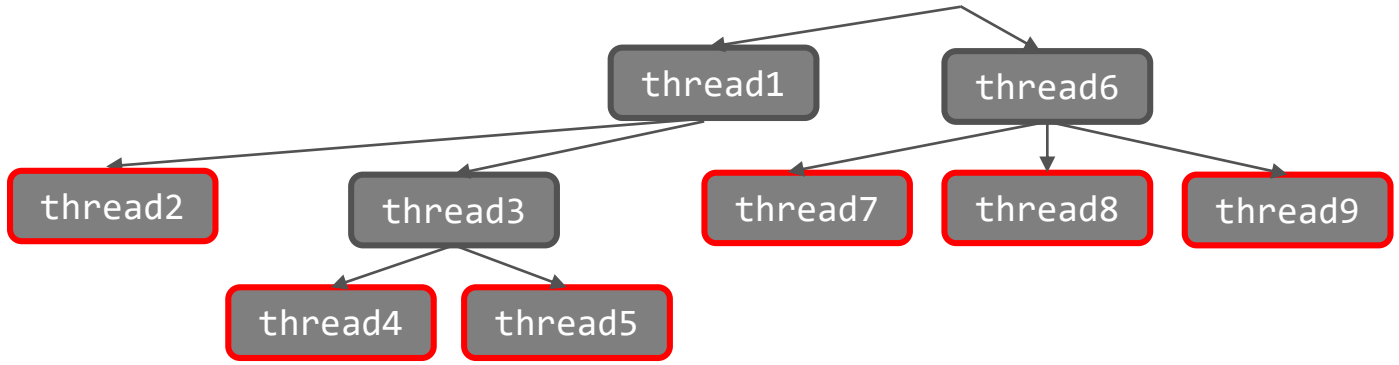


3. Waiting for communication.
   - Graph500: fine-grained MPI program
     ULTs conditionally call MPI functions.



1. ExaFMM: Recursive Parallelism

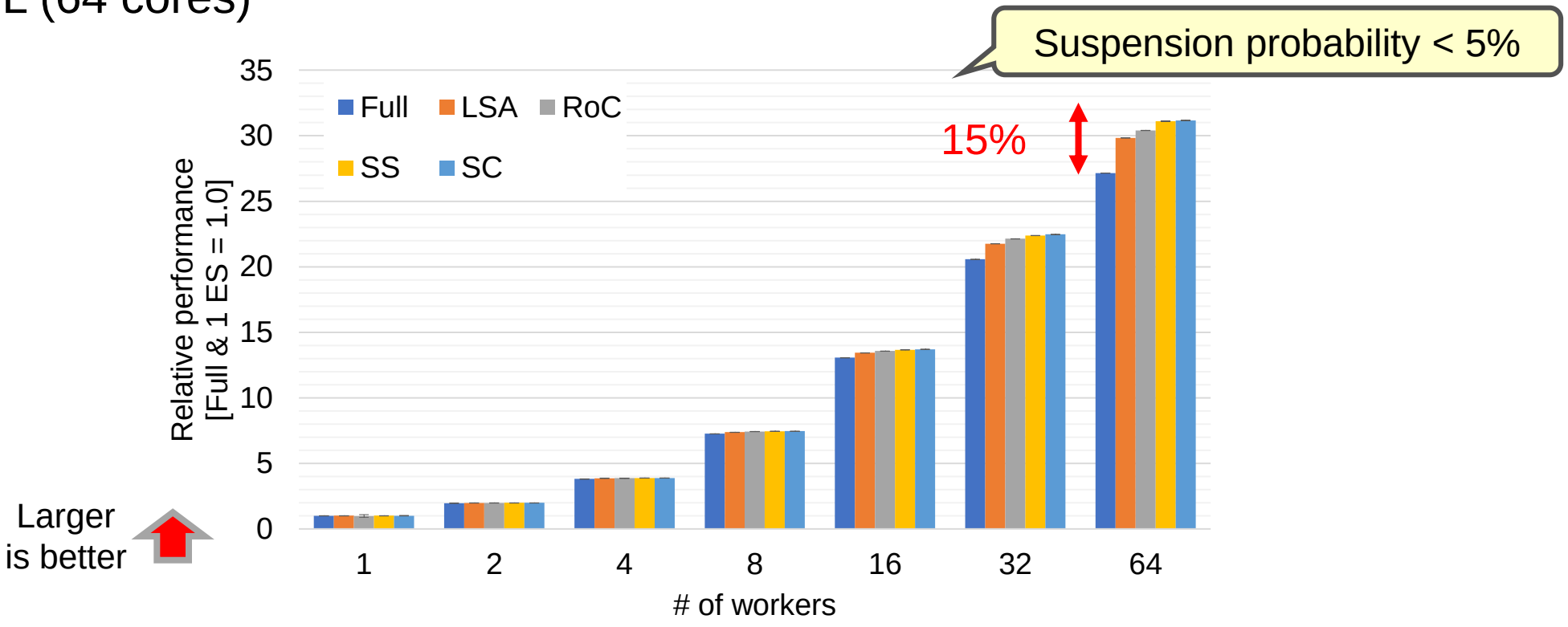
```
void task(void* arg) {
  if (is_leaf(arg))
    calc(arg)
  else {
    for (...)
      create task(...);
    join_all;
  }
}
```



- ExaFMM: Optimized O(N) N-body solver.
- Parent ULTs need to suspend if child ULTs do not finish at `join_all`.
- However, leaf ULTs never suspend since they do not join.
  - Suspension rarely happens ➡ dynamic promotion techniques should perform better!

1. ExaFMM: Performance

- Keep “# of ULTs / worker” for load balancing and increase # of workers on KNL (64 cores)



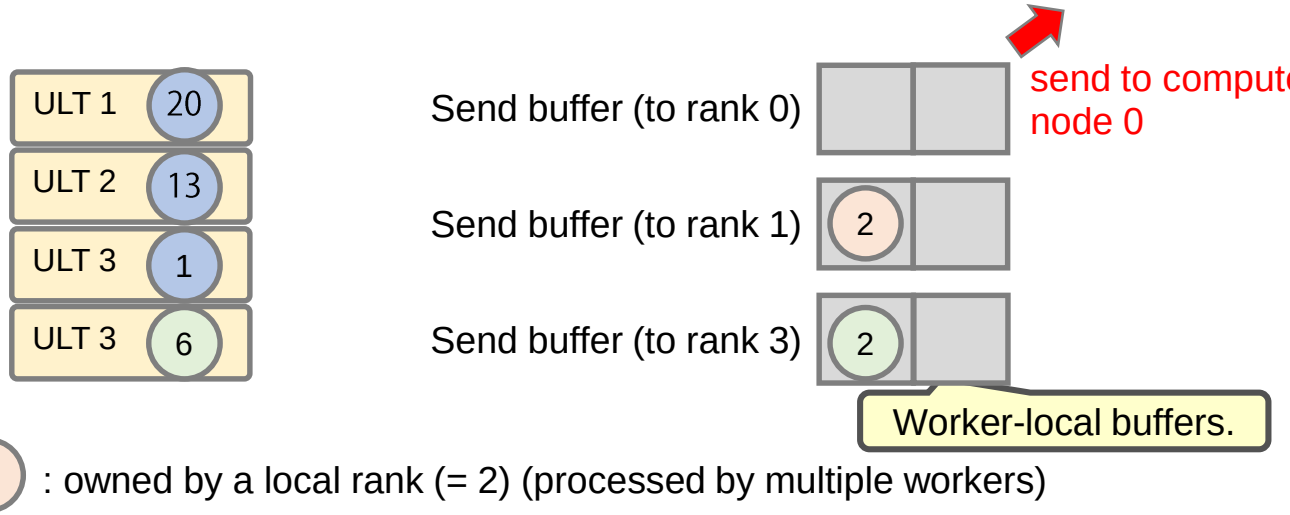
- Performance: **Full** < **LSA** < **RoC** < **SS, SC**

Dynamic promotion performs better.

2. Graph500: Latency Hiding

- `MPI_MULTIPLE_THREADS` on ULT-Aware MPI : one process per node
- Fine-grained Graph500: graph traversal on multiple nodes.
  - One ULT deals with one update vertex.

```
void update(int64_t vindex) {
  int owner_rank = get_owner(vindex);
  if (owner_rank == my_rank) {
    [...]; // update local graph
  } else {
    if (send_buffer.is_full())
      [MPI calls]; // might suspend!
    send_buffer[owner_rank].push(vindex);
  }
}
```



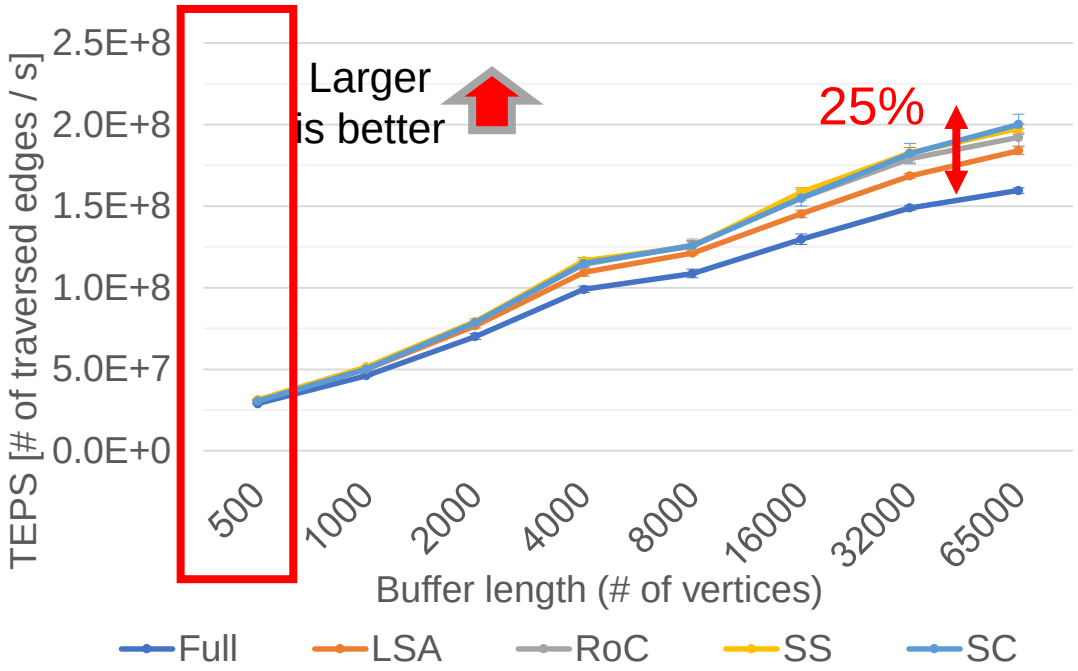
Only when the buffer is full, ULTs can suspend in MPI calls.

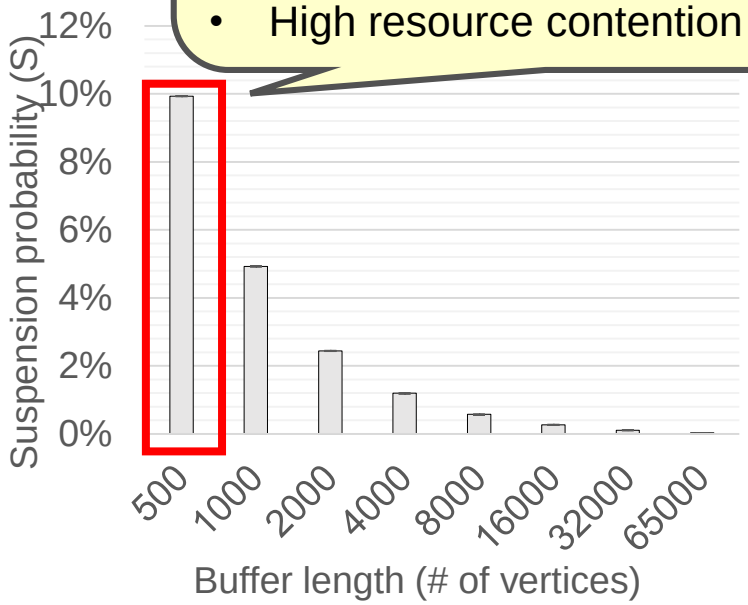
➡ If send buffer is large, only few ULTs suspend!

Omit the explanation on the receiver side.

2. Graph500 : Performance

- 16 KNLs (1K cores in total) + Omni-Path (MPICH3.2.x + CH3 OFI1.4.0 + PSM2)
  - The send buffer size is changed.





When S is high, Full might perform better.
However, threading overheads are negligible because of *other performance issues causing suspension*
- High resource contention

- Performance: **Full** < **LSA** < **RoC**, **SS**, **SC**

Dynamic promotion performs better.

Conclusion: Lessons Learned from Analysis

	Nonsuspension Case			Suspension Case		
	Change Stack?	# of ctx switches	Overhead	Rerun sched.?	Overhead	Constraints
Full	Yes	2	High	No	Low	No
LSA	Yes	2		No		No
RoC	Yes	1		No		No
SS	Yes	0		Yes		*
SC	No	0		Yes	High	**
RtC	No	0	Low	-	-	***

* Schedulers must be stateless.
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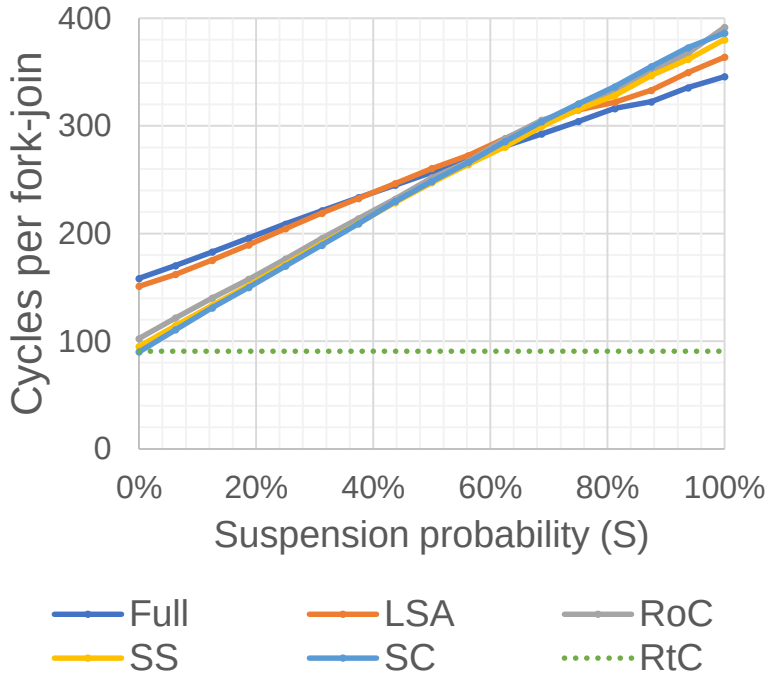

- Trade-off between S=0% performance and functionality
- Trade-off between S=0% and S=100% performance
- RoC shows a good trade-off
  - Full threading capability + good S=0% performance

Argobots 1.0rc employs RoC:
- http://www.argobots.org/
- https://github.com/pmodels/argobots

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.

Future Work

1. Automatic selection of those techniques
   - Runtime selection based on profiling?
2. Investigating overheads of other factors
   - Scheduling policy, memory allocators, thread pools…
3. Higher-level runtime systems
   - Apply those techniques to OpenMP
     - Can we simply apply our techniques?
     - Do OpenMP parallel units have other fundamental overheads?

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