Performance Optimizations

Chapel Team, Cray Inc.
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Outline

- Task Spawning Case Study
- Qthreads Hybrid Waiting
- Stack-Allocate Argument Bundles
- Bounded Coforall Optimization
- Task Spawning Summary
- Other Performance Optimizations

Task Spawning Case Study

LCALS: Background

- **LCALS: Livermore Compiler Analysis Loop Suite**
  - Loop kernels designed to measure compiler performance
  - Developed by LLNL
  - https://codesign.llnl.gov/LCALS.php

LCALS Code
Richard D. Hornung
LCALS version 1.0
LLNL-CODE-638939
2013

- **30 kernels total (11 have parallel variants)**

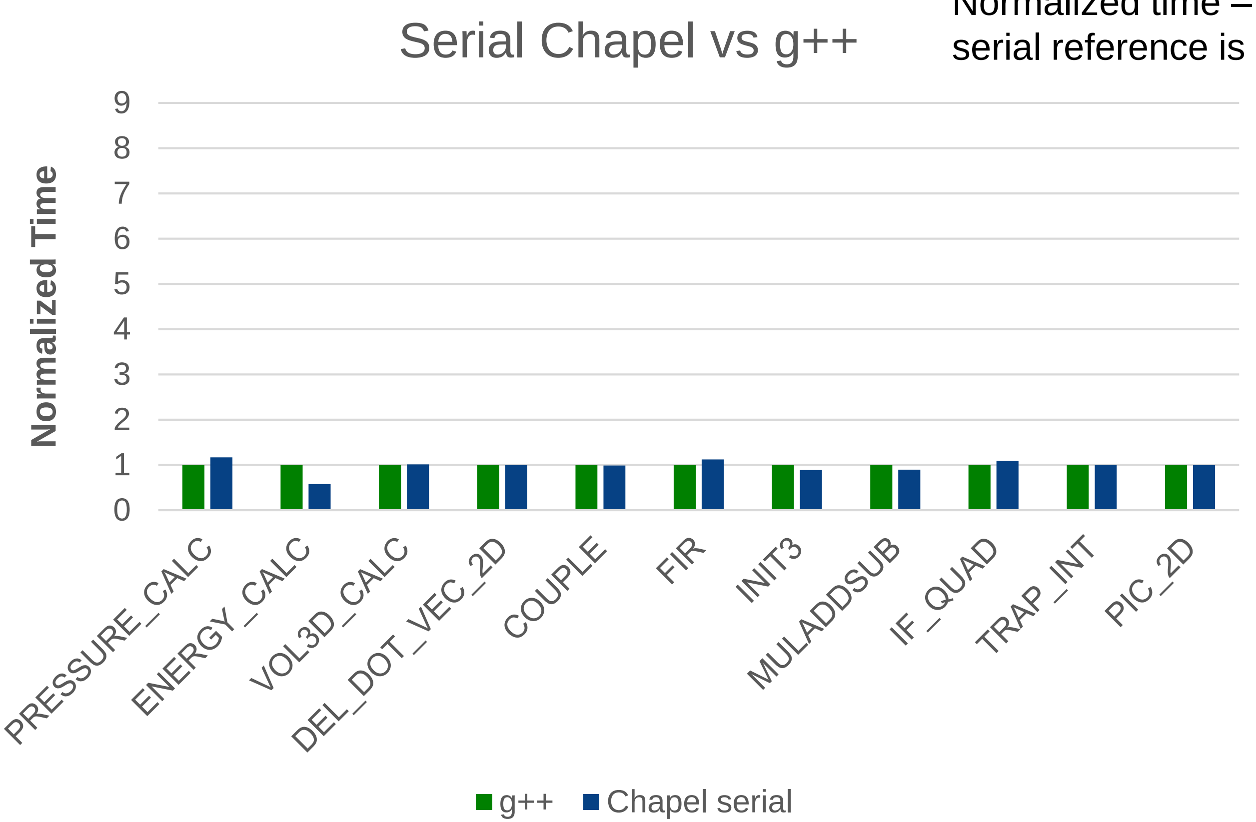
- **Each kernel is run for three sizes (Short, Medium, Long)**

- **Ported LCALS to Chapel in the 1.12 timeframe**
  - first released with Chapel 1.13
  - used to identify performance bottlenecks
  - current port is a pretty direct transliteration

LCALS: Background

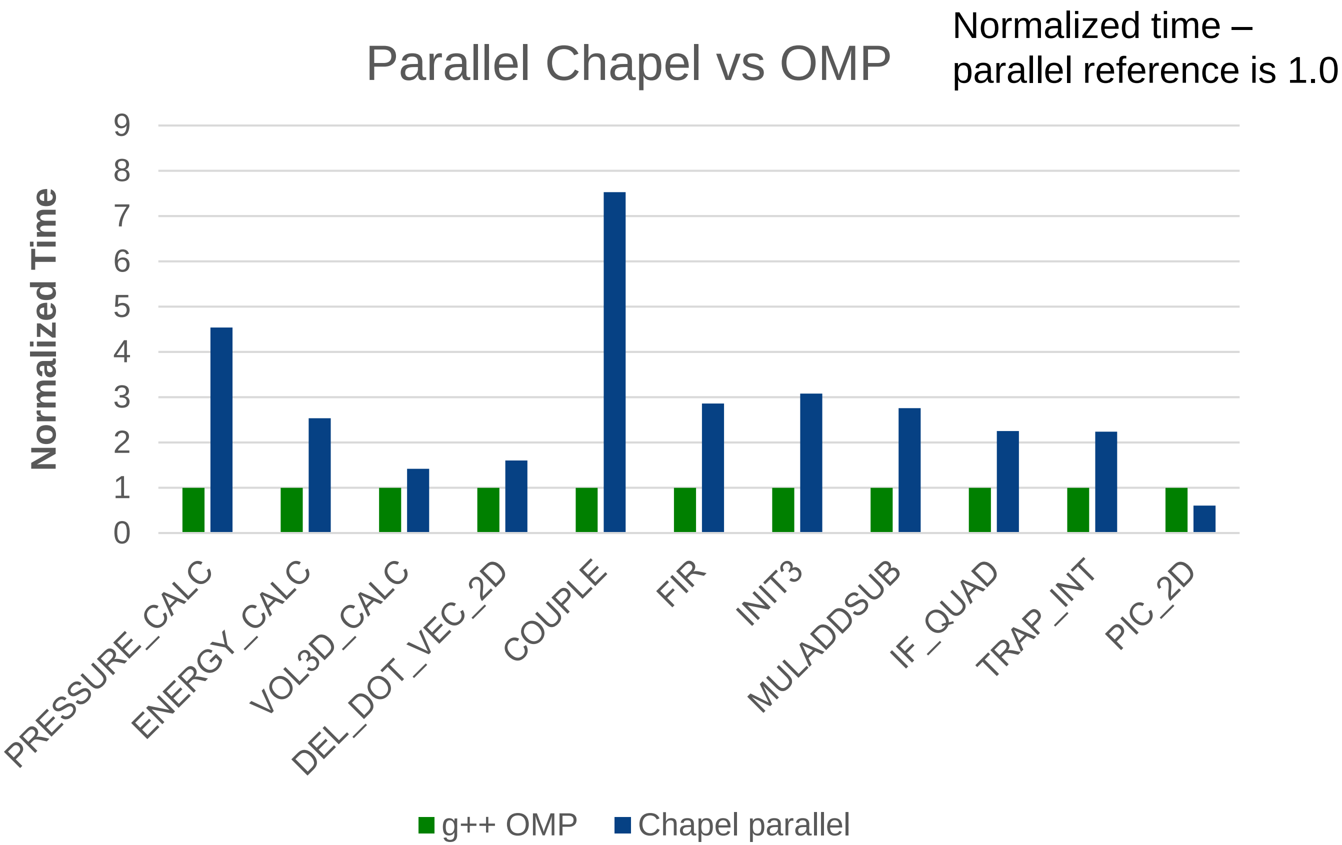
- **Serial performance on par with the reference since 1.14**
  - result of several array optimizations

Normalized time –
serial reference is 1.0



LCALS: Background

- **Parallel variants still lagged behind the reference in 1.14**
  - between 1.5X and 8X slower for long problem size



LCALS: Background

- **Discovered that most of the time is spent spawning tasks**
  - conceptually, kernels perform a simple parallel idiom in a trial-loop
    - e.g. code for the MULADDSUB kernel

Chapel

```
for 0..#num_samples {
  forall i in 0..#len {
    out1[i] = in1[i] * in2[i];
    out2[i] = in1[i] + in2[i];
    out3[i] = in1[i] - in2[i];
  }
}
```

C/C++ OpenMP

```
for (s=0; s<num_samples; ++s) {
  #pragma omp parallel for
  for (i=0 ; i<len ; i++) {
    out1[i] = in1[i] * in2[i];
    out2[i] = in1[i] + in2[i];
    out3[i] = in1[i] - in2[i];
  }
}
```

LCALS: Background

- **Discovered that most of the time is spent spawning tasks**
  - conceptually, kernels perform a simple parallel idiom in a trial-loop
    - e.g. code for the MULADDSUB kernel
  - exacerbated for the “short” problem size

Long Problem Size

```
// Modest num trials, modest trip count
for 0..#12000 {
  forall i in 0..#44217 {
    ...
  }
}
```

Short Problem Size

```
// huge num trials, tiny trip count
for 0..#15000000 {
  forall i in 0..#171 {
    ...
  }
}
```

Task Spawning: Background

- **Decided to focus on improving task spawning speed**
  - created a no-op task-spawn micro-benchmark to investigate
    - Chapel, OpenMP, and native qthreads variants

Chapel

```
for 1..trials do
  forall 1..cores do ;
```

OpenMP

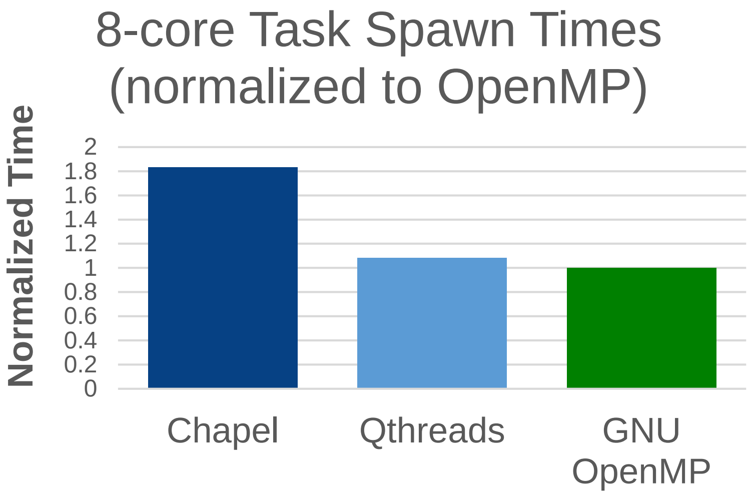
```
for (i=0; i<trials; i++)
  #pragma omp parallel for
  for (j=0; cores; j++) { }
```

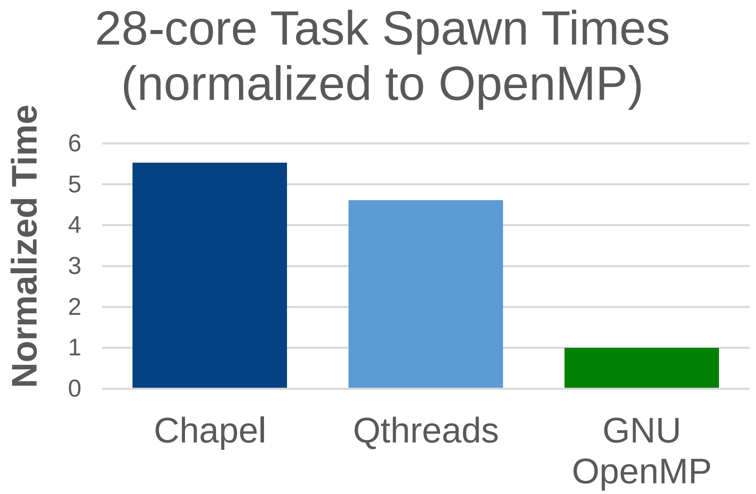
Qthreads

```
for (i=0; i<trials; i++) {
  qthread_incr(&endCount, cores)
  for (j=0; j<cores; j++)
    qthread_fork(decEndCount, ...);

  while (endCount != 0) qthread_yield();
}
```

Task Spawning: Background

- **Results of task spawning micro-benchmark with 1.14:**
  - performance wasn't too far off for lower core-count machines
    - run on an 8-core (16 HT) Nehalem node, with gcc 6.3
    - Chapel within 80% of OpenMP, qthreads within 10%
  - performance was further off of OpenMP for high core-count machines
    - run on a 28-core (56 HT) Broadwell node, with gcc 6.3
    - Chapel was ~6x slower than OpenMP, qthreads was ~5x slower





Task Spawning: Background

- **Task spawning performance goals for this release:**
  - determine if qthreads can be competitive with OpenMP
    - if not, need to explore other tasking layer options
  - minimize tasking overhead that Chapel introduces
    - minimize overhead introduced by the compiler, modules, runtime shim

Qthreads Hybrid Waiting

Hybrid Waiting: Background

- **Idle workers have 2 mechanisms to wait for work**
  - set at qthreads configure time:
    - spinwait (busy-waiting -- continuous spinloop)
    - condwait (sleep -- uses a pthread condwait)

- **Our default wait-policy was condwait**
  - chosen while investigating qthreads as our default over fifo
    - spin-waiting killed performance of single/low-threaded codes
  - condwait hurt performance of some highly-parallel code
    - but not dramatically, investigation done on an 8-core machine

- **Determined that pure condwait hurts task-spawn speed**
  - significant penalty on high core-count machines
  - needed to implement a new waiting mechanism

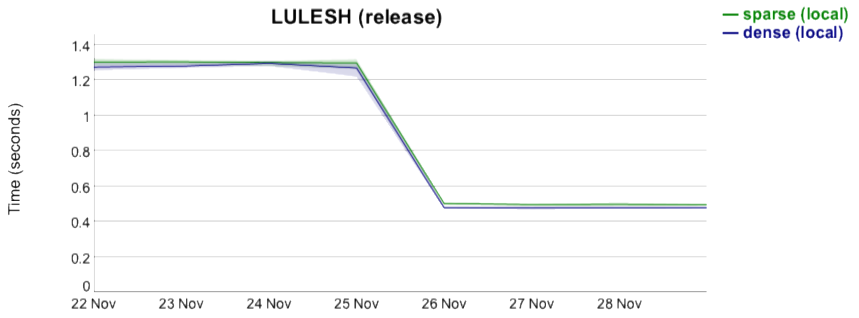
Hybrid Waiting: This Effort

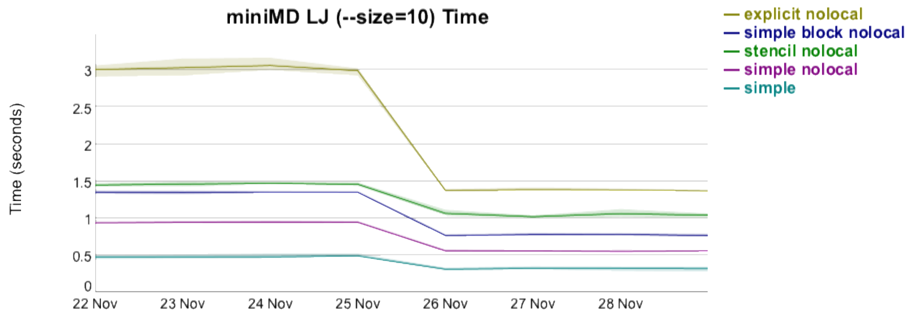
- **Implemented a hybrid spin/condwait scheme**
  - conceptually simple
    - spin for some amount of time before giving up and sleeping
  - difficult part was choosing spin duration

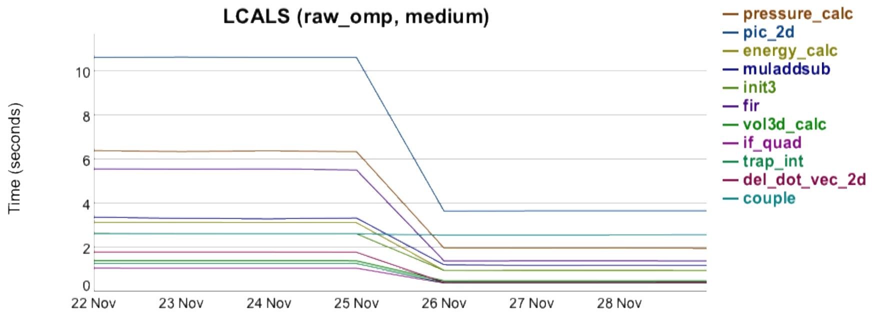
- **Current strategy: spin 300,000 times before sleeping**
  - opted for a spincount-based strategy (instead of a time-based)
    - low overhead, easy to implement
  - experiments showed 100k-300k provided best task-spawn perf
  - went with the upper bound, since Chapel is a parallel language
    - also happens to match GNU OpenMP spincount policy
  - on Crays, default is bumped to 3,000,000
    - applications that warrant a Cray are likely to be very parallel

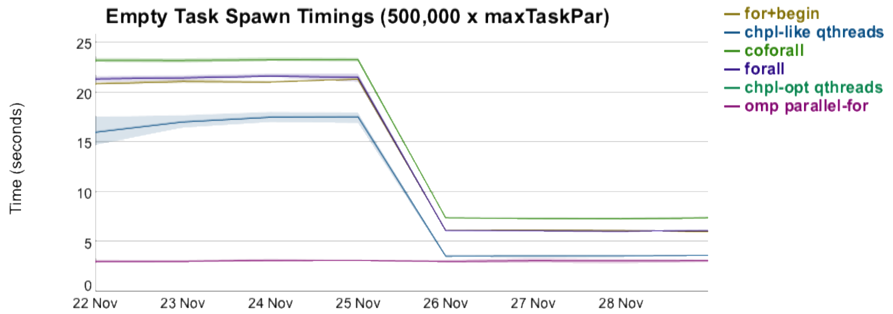
Hybrid Waiting: Impact

- **Resulted in significant performance improvements**
  - particularly for single-locale programs



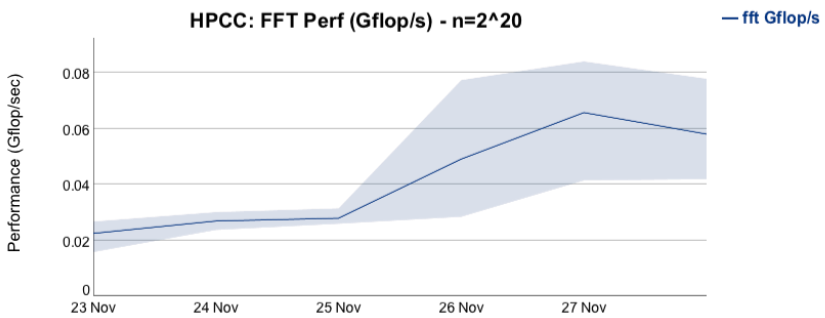


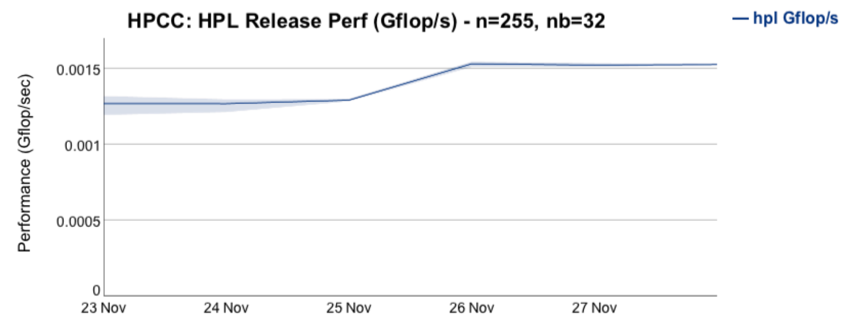


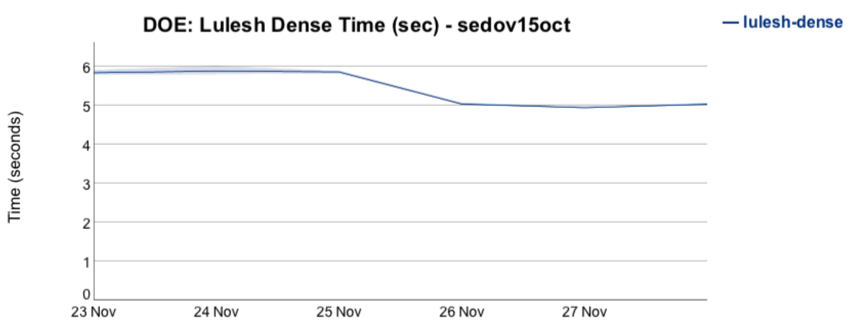


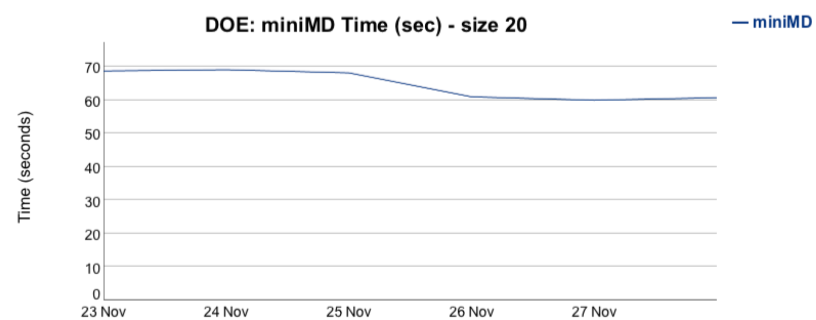
Hybrid Waiting: Impact

- **Resulted in significant performance improvements**
  - some nice multi-locale improvements as well
    - bumping spincount on Crays further improved fft/hpl (not shown here)



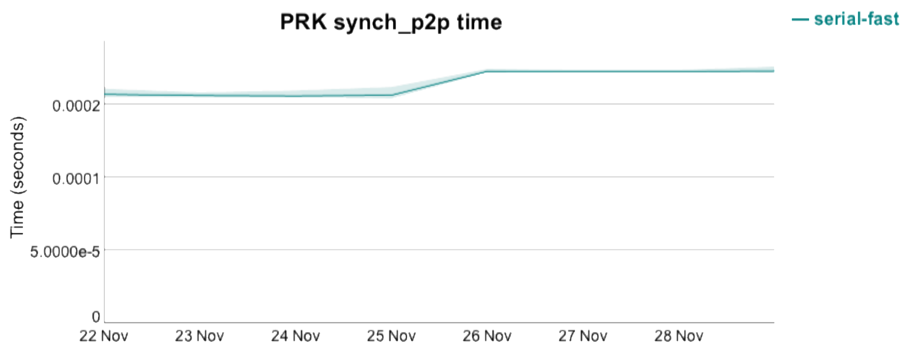


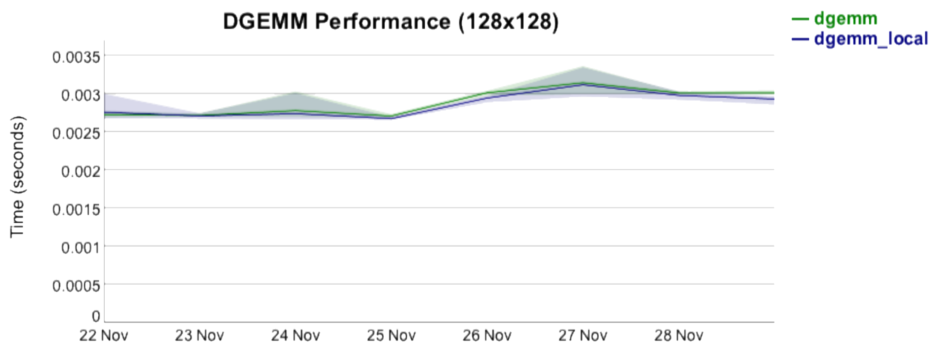




Hybrid Waiting: Impact

- **Some minor regressions**
  - for short-lived minimally-parallel benchmarks
    - acceptable in light of improvements on highly-parallel benchmarks





Hybrid Waiting: Status and Next Steps

Status:

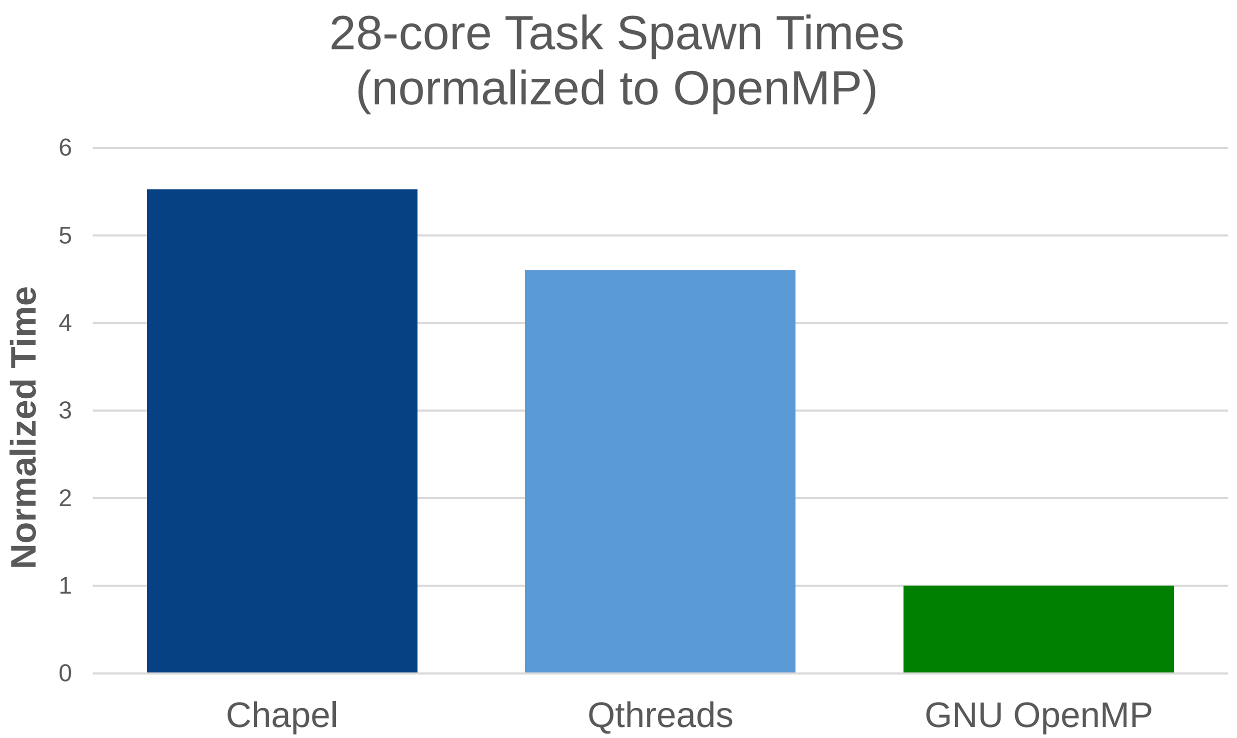
- Hybrid spin/condwait scheme implemented
  - contributed upstream
- Significantly improved speed of task-spawning
  - without seriously hurting serial applications

Next Steps:

- Add a friendlier user-facing policy mechanism
  - e.g. WAIT_POLICY={active, passive} vs. SPINCOUNT=30000
- Implement spin-wait policy across qthreads schedulers
  - currently nemesis (flat) only, need to expand to distrib (numa)
- Explore time-based spinning strategies
  - may offer a more “portable” balance across architecture
  - Intel’s OpenMP runtime uses a time-based strategy

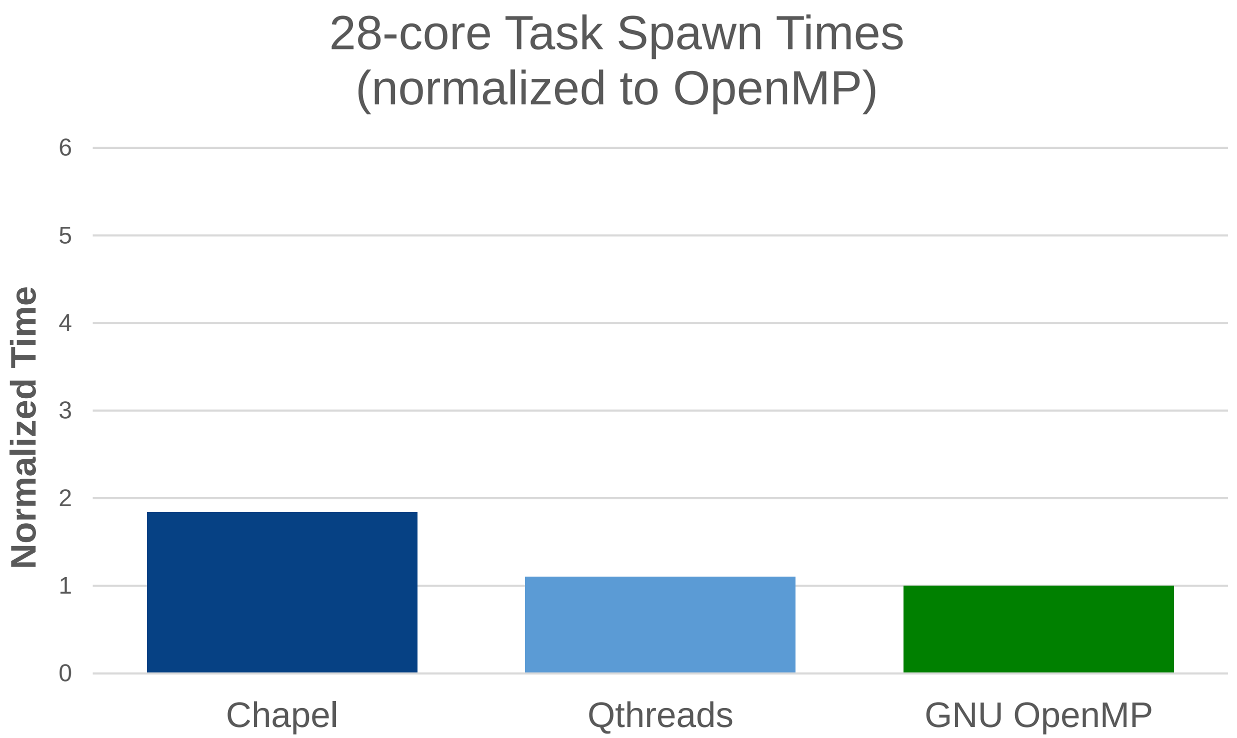
Hybrid Waiting: Task Spawning Impact

- **Previously Chapel and qthreads lagged behind OpenMP**



Hybrid Waiting: Task Spawning Impact

- **Hybrid waiting significantly closes the gap with OpenMP**
  - 3x faster: Chapel within ~80% of OpenMP, qthreads within 10%
    - next step is to reduce Chapel's overhead



Stack-Allocate Argument Bundles

Stack Arg Bundles: Background

- **on/begin/cobegin/coforall create argument bundles**
  - on-statement and task bodies are outlined
  - runtime calls outlined function in new task or on remote locale
  - argument bundles store variables to be passed to the outlined function

- **Generated code heap-allocated argument bundles**
  - adding overhead to tasks, on-statements

- **Heap allocation was redundant**
  - fifo allocated a task descriptor and could store arguments there
  - qthreads already had the ability to copy arguments into new task
  - comm layers needed to copy bundle in some cases
    - caller could free argument bundle immediately
    - but comm/tasking could delay call to outlined function & use of bundle

Stack Arg Bundles: This Effort

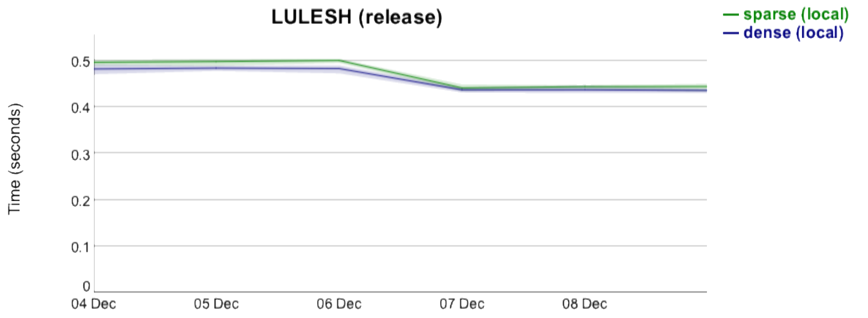
- **Adjust compiler to stack-allocate argument bundles**

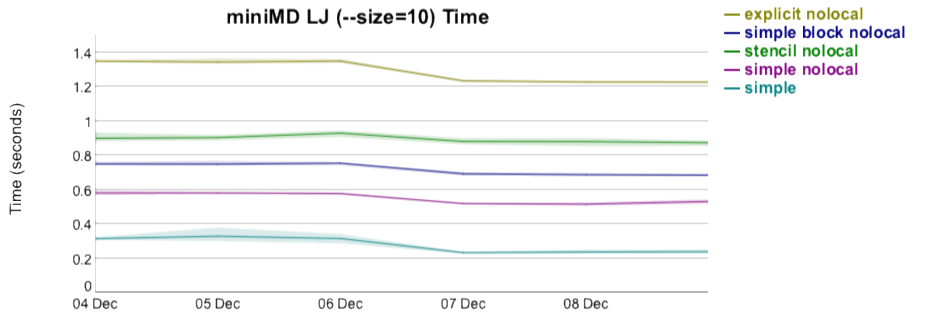
- **Further minimize copying within the runtime**
  - runtime often needs to add information to argument bundle
    - e.g. which function to run on remote locale
  - this should be contiguous in memory with argument bundle
    - e.g. to send in one network message
  - solution: include a struct for runtime information in the bundles…
    … to completely avoid heap-allocating or copying in many cases

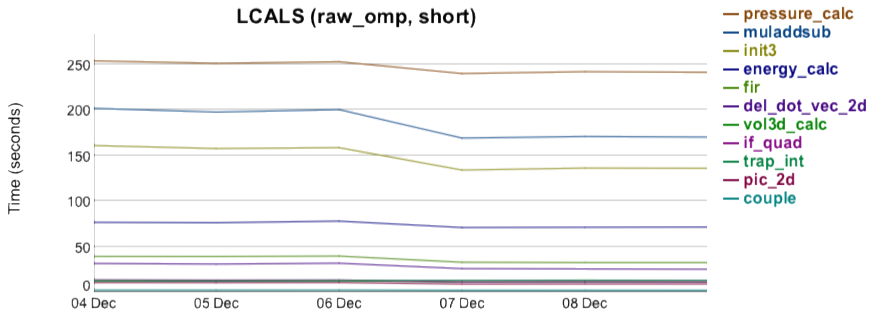
- **Adjust runtime to work with stack-allocated arg bundles**
  - including all tasking and communication layers
    - fifo, qthreads, muxed, ugni, gasnet
  - while there, minimized heap allocation calls in tasking & comms

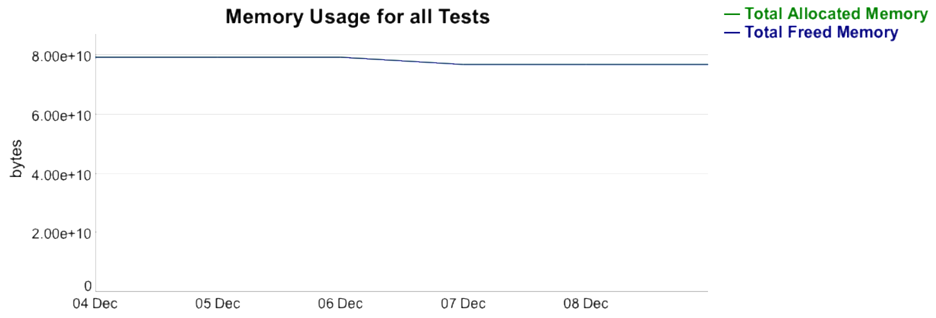
Stack Arg Bundles: Impact

- **Resulted in single-locale speedups**
  - and a decrease in the total amount of memory allocated



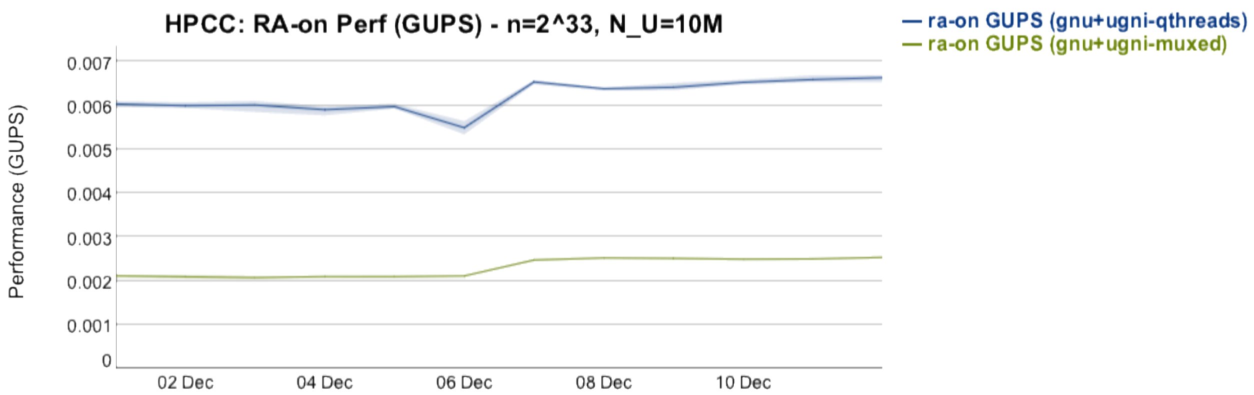






Stack Arg Bundles: Impact

- **10-15% improvement for multi-locale RA-on**
  - RA-on creates many on statements
  - stack-allocating reduced on statement overhead



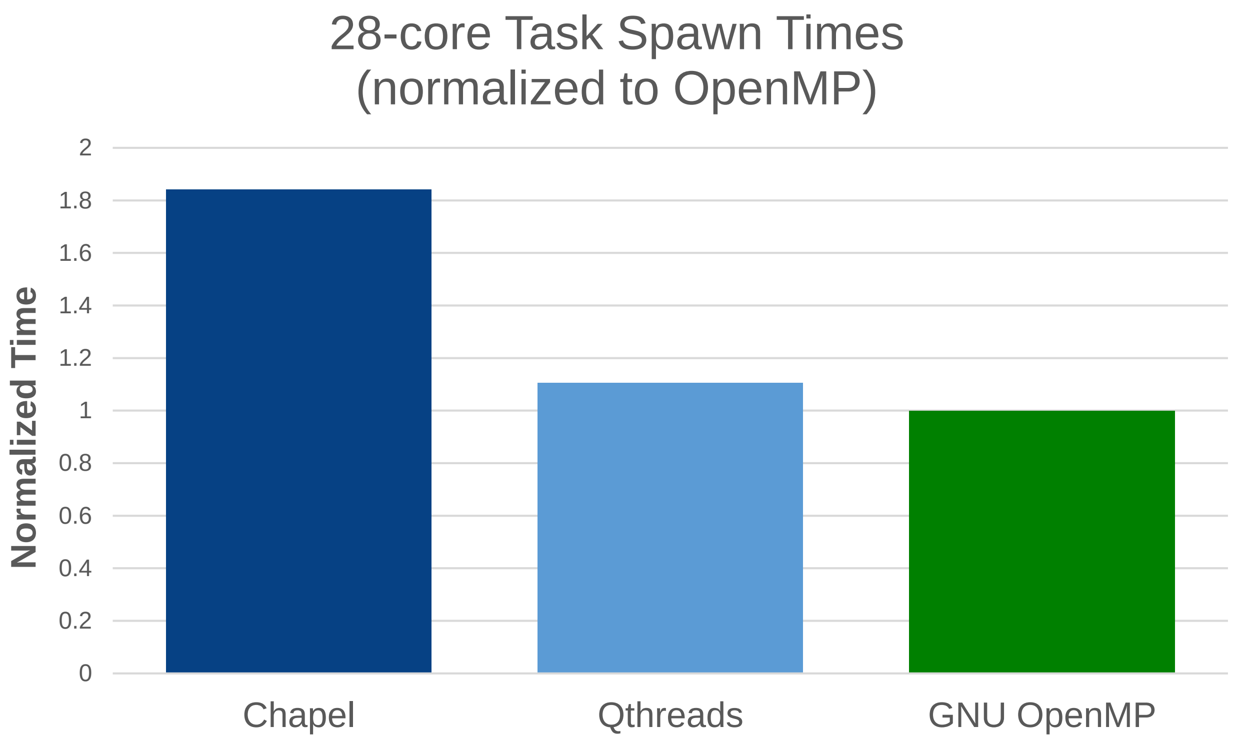
Stack Arg Bundles: Next Steps

Next Steps:

- Remove other unnecessary heap allocation in generated code
- Consider a heap-to-stack compiler optimization

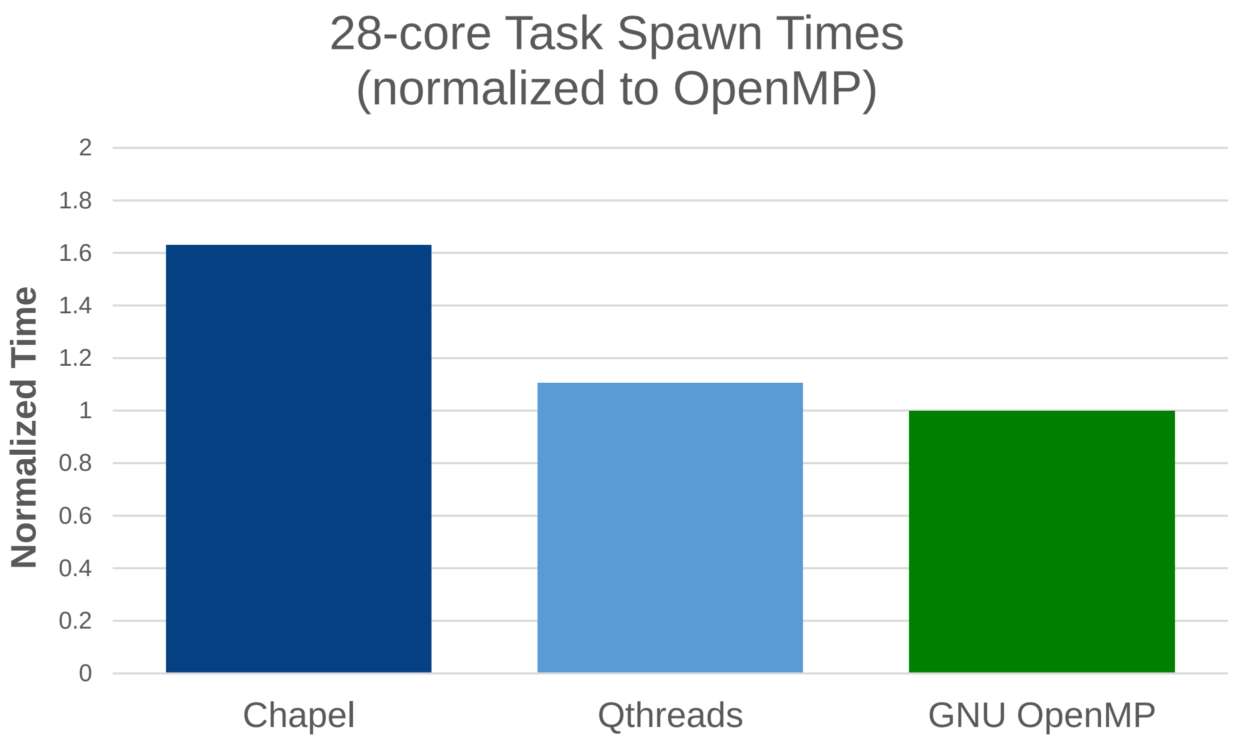
Stack Arg Bundles: Task Spawning Impact

- Chapel was within ~80% of OpenMP



Stack Arg Bundles: Task Spawning Impact

- **Stack allocating arg bundles reduces Chapel's overhead**
  - now within 60% of OpenMP



Bounded Coforall Optimization

Bounded Coforall: Background

- Coforalls are transformed by the compiler, from:

```
coforall i in 1..10 { body(); }
```

roughly into:

```
var endCount: atomic int;
for i in 1..10 {
  endCount.add(1);                    // note: incrementing once per task
  spawnTask(bodyWrapper, endCount);
}
endCount.waitFor(0);

proc bodyWrapper(endCount) {
  body();
  endCount.sub(1);
}
```

Bounded Coforall: This Effort

- **Minimize end-count manipulation for “bounded” coforalls**
  - “bounded” coforalls have a known trip-count (range/domain/array)

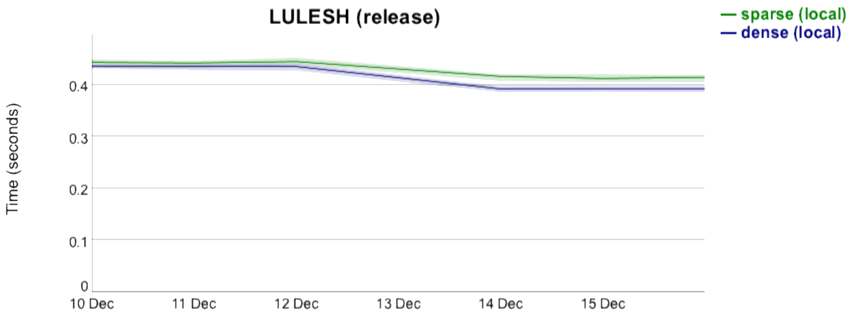
```
coforall i in 1..10 { body(); }
```

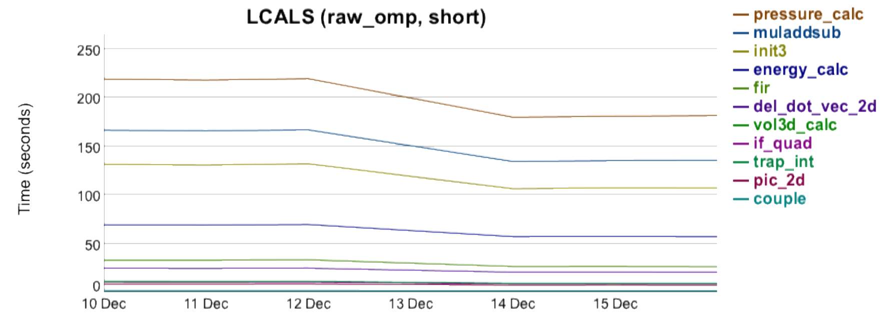
now roughly converted to:

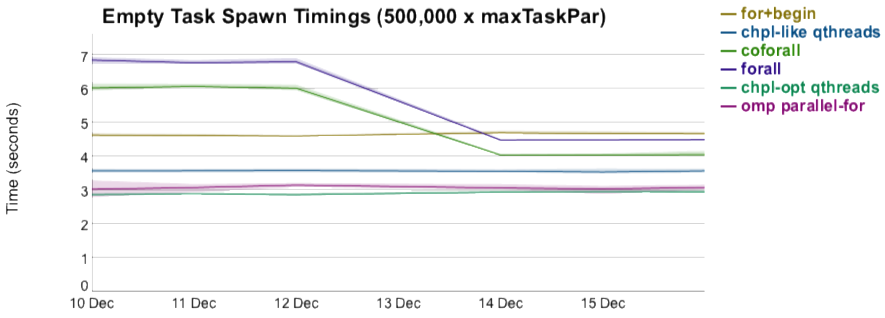
```
var tmpIter = 1..10;
var numTasks = tmpIter.size
var endCount: atomic int;

endCount.add(numTasks);   // single atomic op vs. op per task
for i in tmpIter {
  spawnTask(bodyWrapper, endCount);
}
endCount.waitFor(0);

proc bodyWrapper(endCount) { /* same as before */ }
```

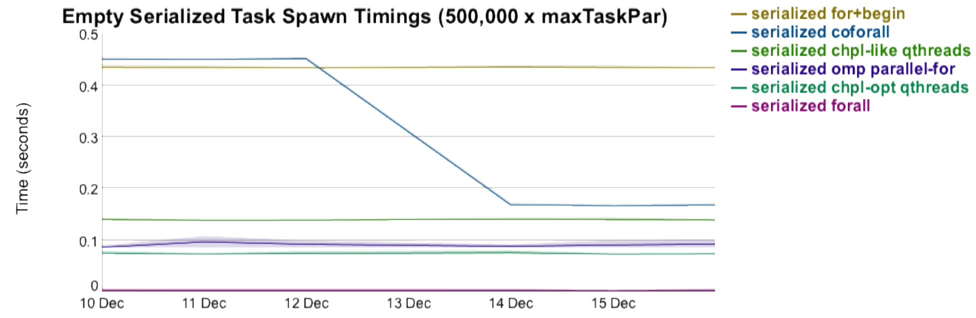
Bounded Coforall: Impact

- **Improved performance for many single-locale benchmarks**
  - no known regressions









Bounded Coforall: Status and Next Steps

Status:

- optimized coforalls over types with a known trip-count
  - currently ranges/domains/arrays
  - only done for "local" coforalls currently

Next Steps:

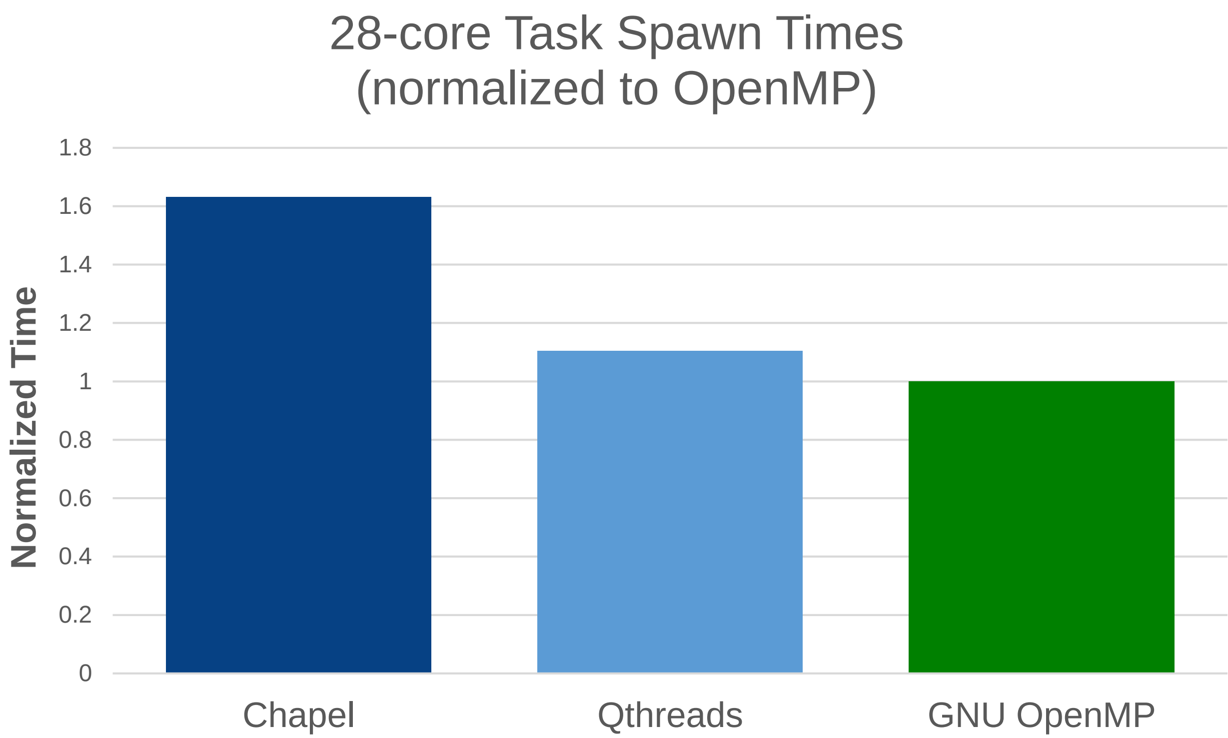
- Implement optimization for "remote" coforalls

```
coforall i in 1..10 do on Locales[i] { body(); }
```

- Add support for "bulk" spawning to our runtime interface
  - single runtime call to spawn all tasks instead of call per task
  - would further minimize overhead introduced by Chapel
- Add support for "bulk" spawning to qthreads
  - likely that this would permit qthreads optimizations

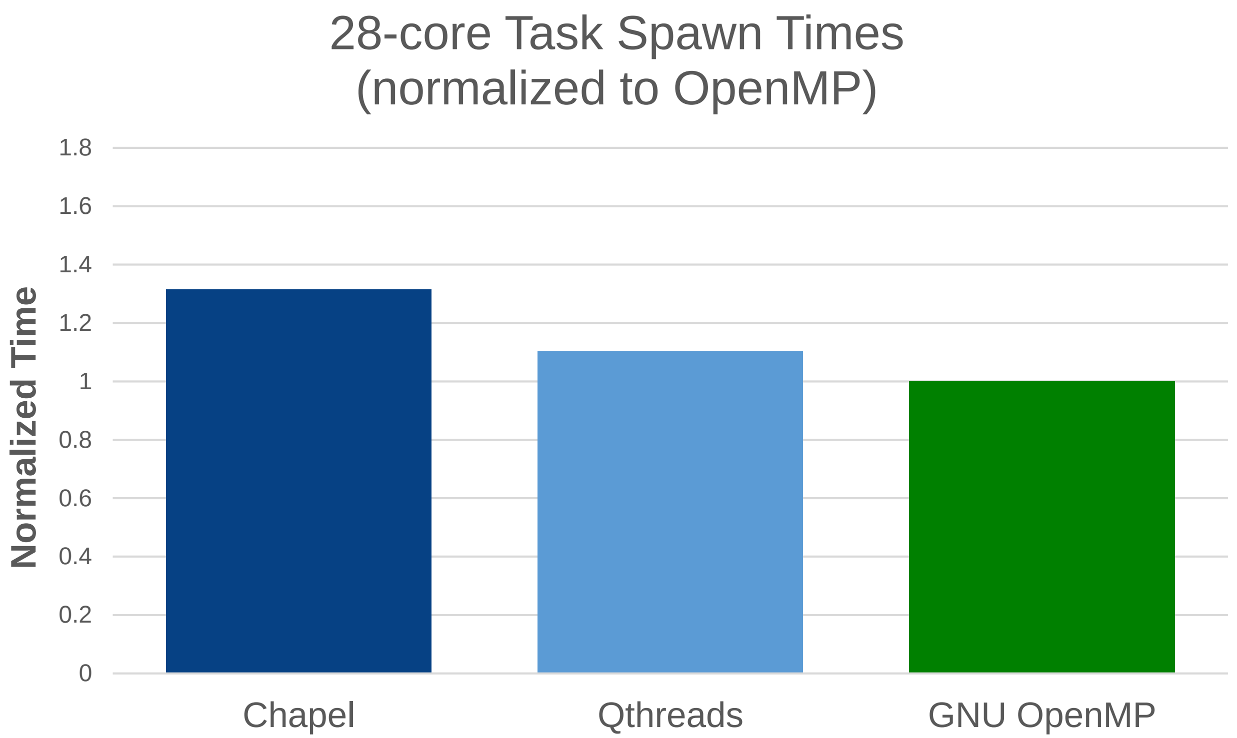
Bounded Coforall: Task Spawning Impact

- Chapel was within ~60% of OpenMP



Bounded Coforall: Task Spawning Impact

- **Coforall optimization further reduces Chapel's overhead**
  - now within 30% of OpenMP



Task Spawning Summary

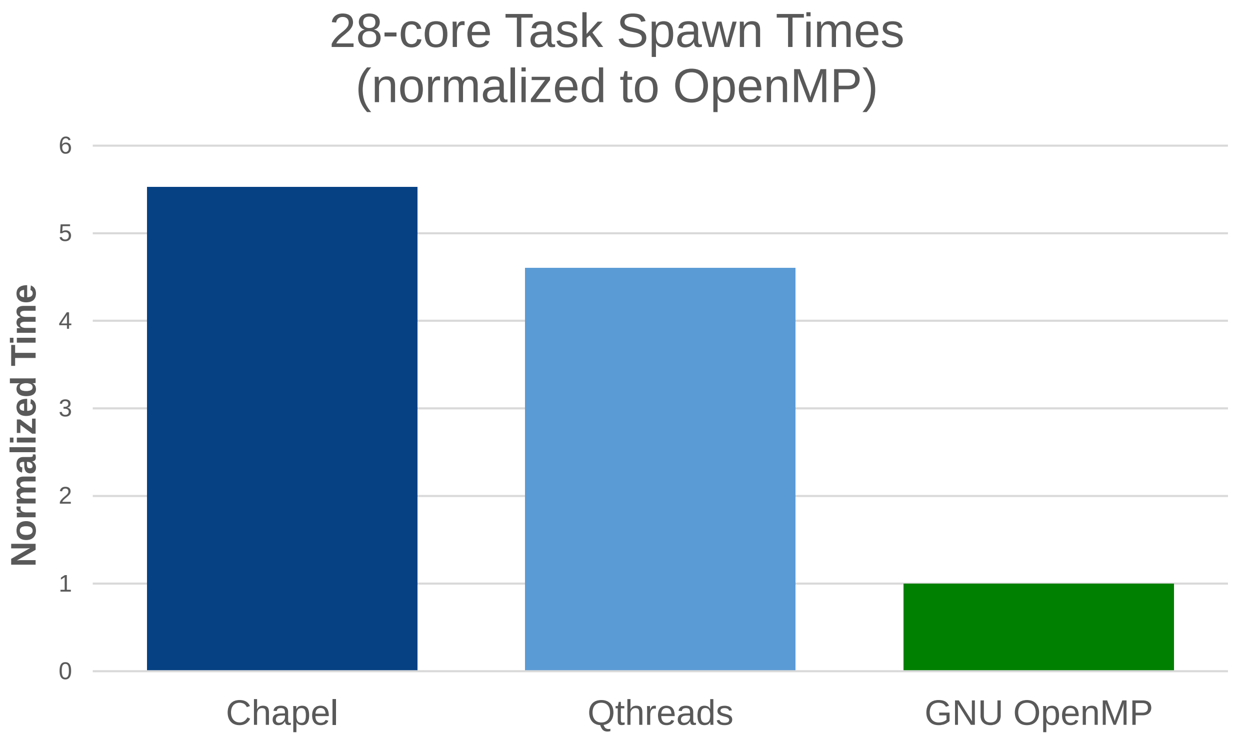
Task Spawning: Summary

- **Task spawning investigation led to several optimizations**
  - implemented a hybrid spin/condwait scheme in qthreads
  - moved argument bundles from the heap to the stack
  - minimized task counting overhead of bounded coforalls

- **Optimizations had a significant impact**
  - large performance improvements for many benchmarks
    - LCALS, MiniMD, Lulesh, SSCA2, and many others
  - task spawning is around 4 times faster now

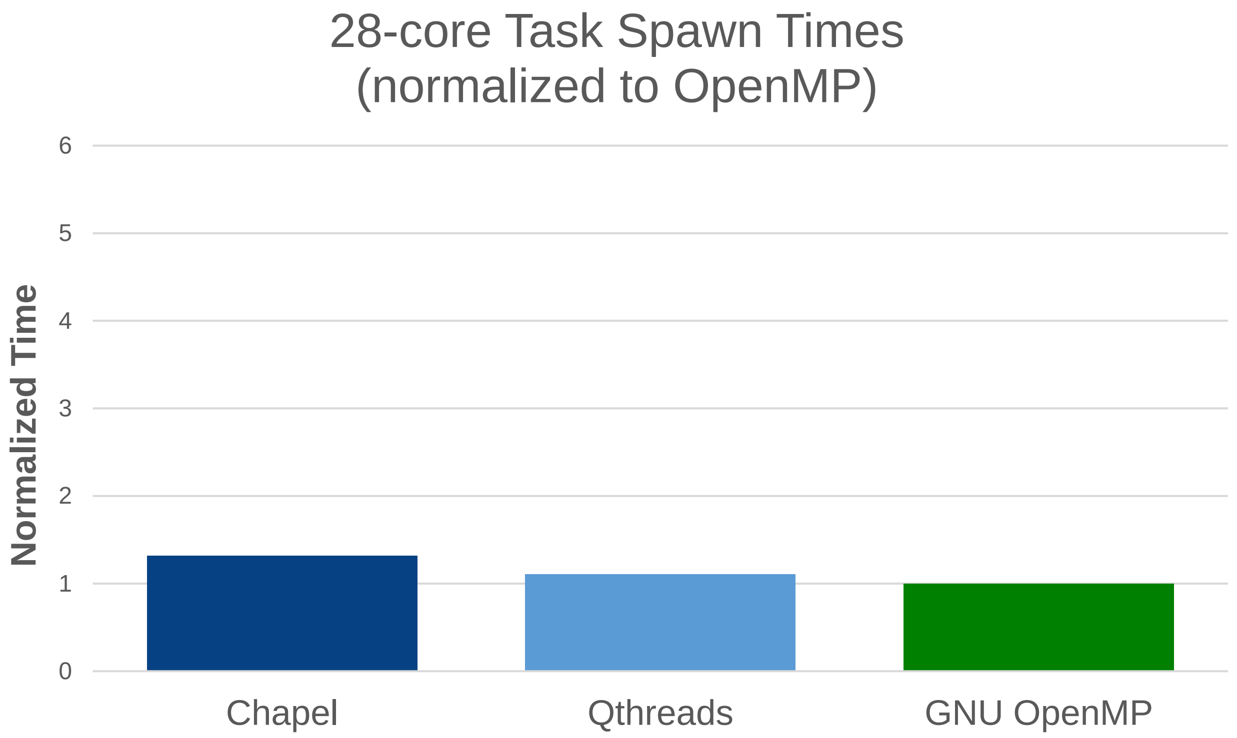
Task Spawning: Performance Impact

- **1.14 task spawning performance**
  - over 5x slower than GNU OpenMP



Task Spawning: Performance Impact

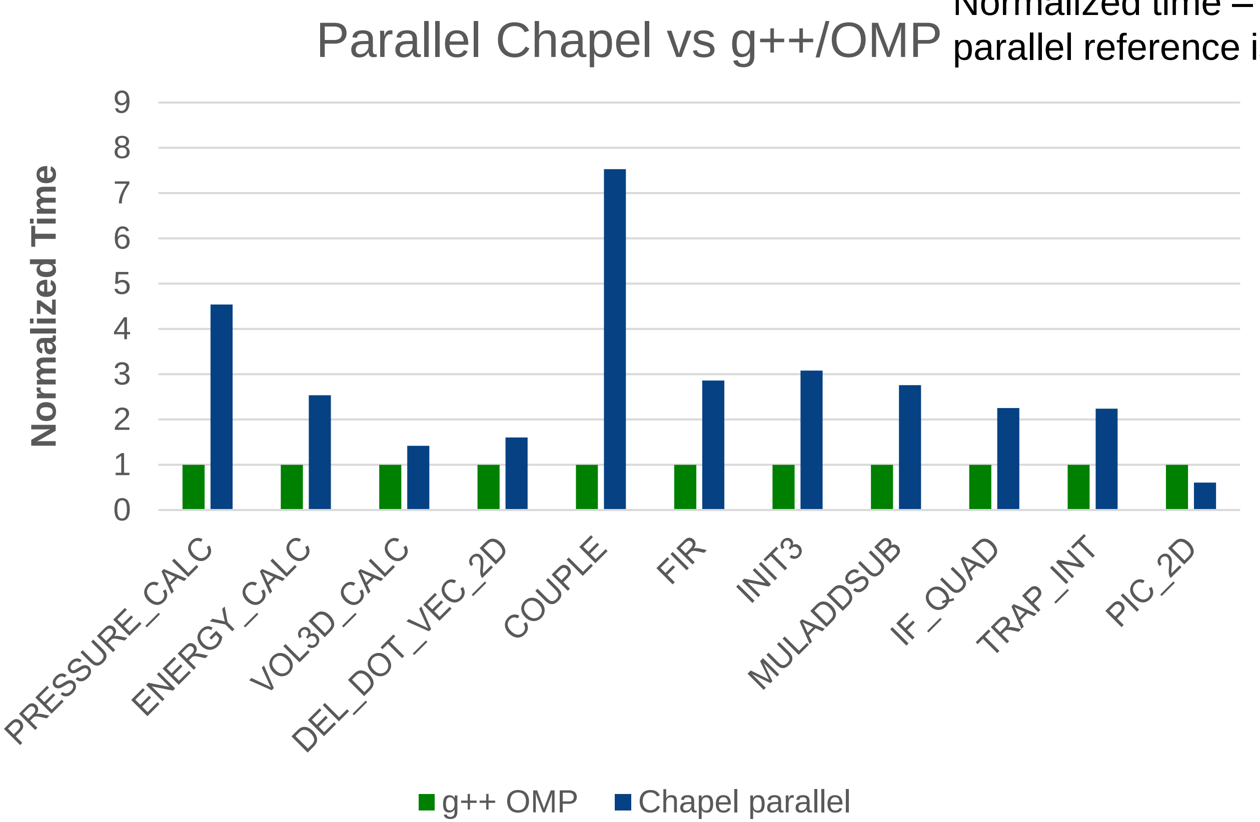
- **1.15 task spawning performance**
  - within 30% of GNU OpenMP for 28-core machine
  - within 5% for 8-core machine (not shown here)



Task Spawning: LCALS Performance Impact

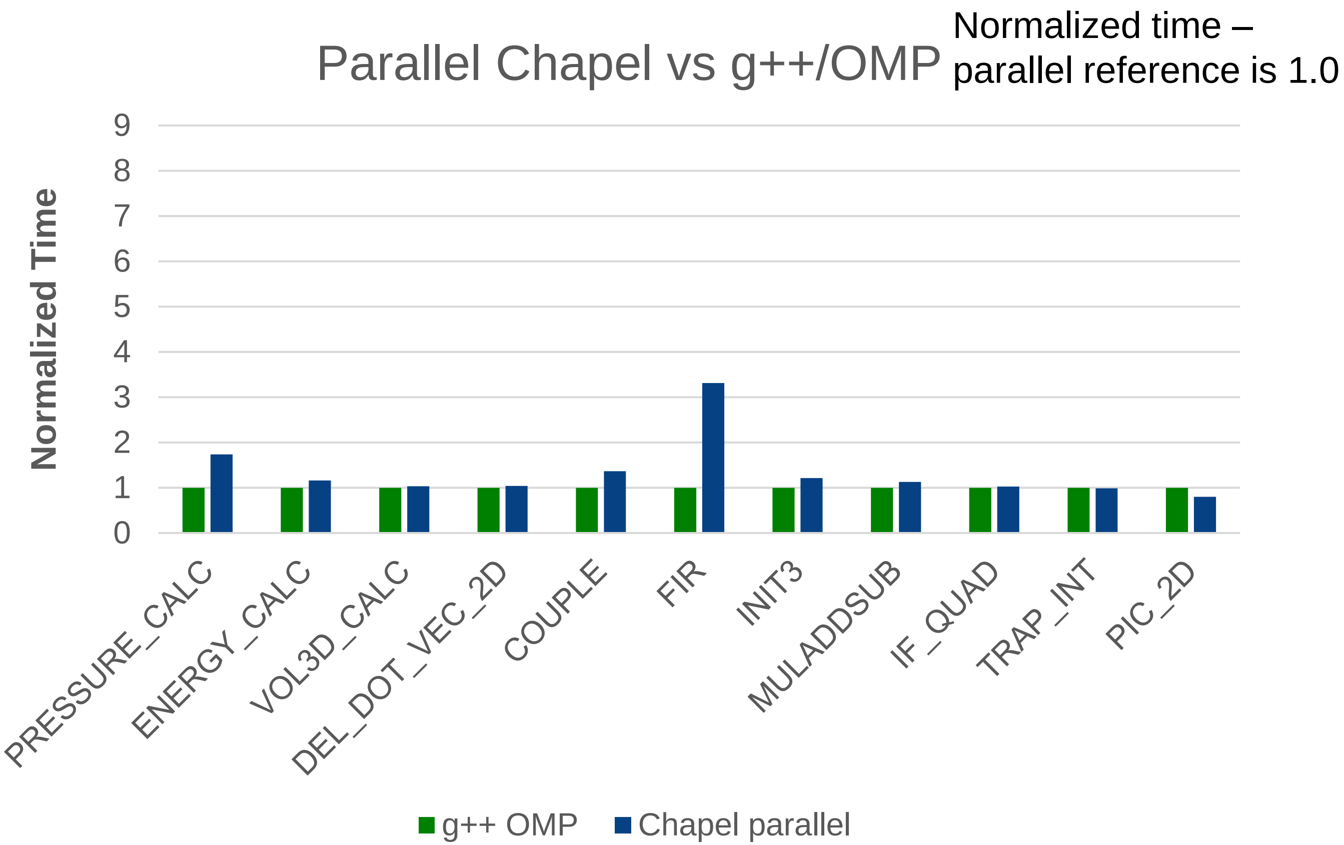
- **1.14 LCALS performance**

Normalized time – parallel reference is 1.0



Task Spawning: LCALS Performance Impact

- **1.15 LCALS performance**
  - ~3-4x speedup: on par or very close to reference for most kernels



Task Spawning: Next Steps

- **Continue to optimize task spawning**
  - minimize Chapel's overhead
    - add a bulk spawning interface to the runtime shim
  - further optimize qthreads
    - add a bulk spawning interface
  - explore alternatives to qthreads?
    - Argobots, Intel's OpenMP runtime, OCR
  - explore different task joining mechanisms
    - alternatives to our current atomic "end count"

- **Add additional task-spawning benchmarks**
  - add a stream-like variant
  - add nested parallelism variants

Other Performance Optimizations

Other Performance Optimizations

- Optimized iteration over 1D strided arrays
- Improved loop invariant code motion optimization
- Improved remote-value-forwarding optimization
- Improved performance of casting strings to numeric types
- Optimized <~> to avoid unnecessary reference counting

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