# Tales from the Trenches: Whipping Chapel Performance into Shape

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# Chapel Performance History

- **Poor performance is Chapel's most common criticism**
  - For most of Chapel, this has been an accurate concern/criticism
- **Performance was significantly behind MPI**
  - And other established HPC technologies (OpenMP, SHMEM, etc.)
- **Performance dramatically improved in recent years**
  - Many core idioms/benchmarks now on par with MPI+X/SHMEM

# A Brief History of Chapel

## Chapel's Infancy: DARPA HPCS (2003–2012)

- Research focus: ~6-7 FTEs
  - distinguish locality from parallelism
  - seamlessly mix data- and task-parallelism
  - support user-defined distributed arrays, parallel iterators

## Chapel's Adolescence: "the five-year push" (2013–2018)

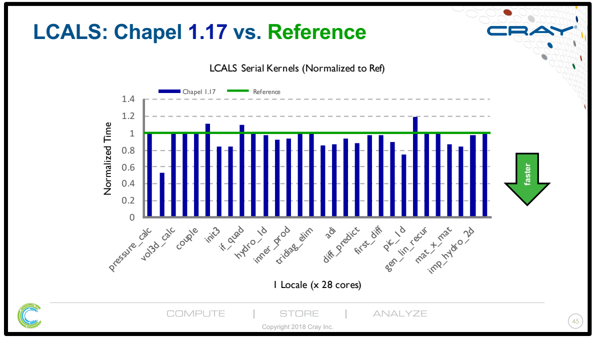
Then Now

- Development focus: ~13-14 FTEs
  - **performance and scalability**
  - **ecosystem:** documentation, libraries, tools, …
  - **base language fixes:** OOP features, error-handling, strings, …

# Plan for this talk

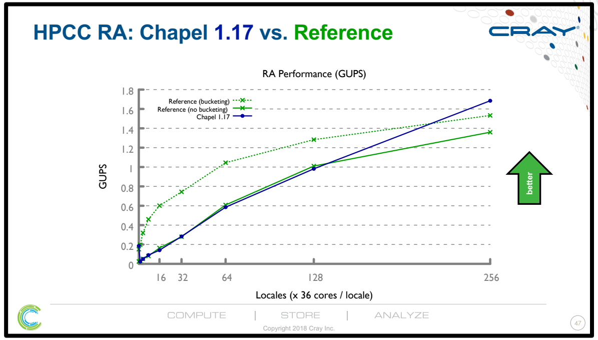
- **Highlight optimizations that closed performance gap**
  - Array Optimizations
  - Runtime Improvements
  - Communication Reductions
- **Showcase benchmark results for key HPC idioms**
  - Comparing **Then** (1.7) vs. **Now** (1.17) vs **Reference**
- **Interrupt if you want details on specific optimizations**

# HPC Patterns




LCALS

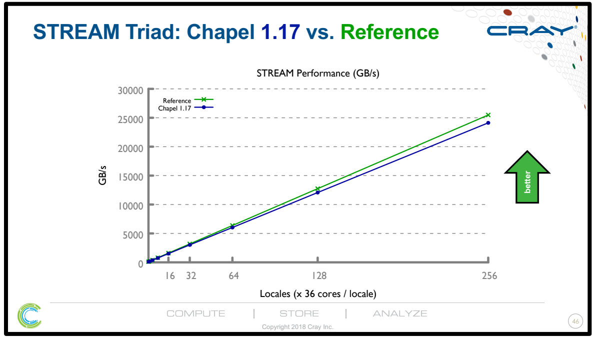
HPCC RA

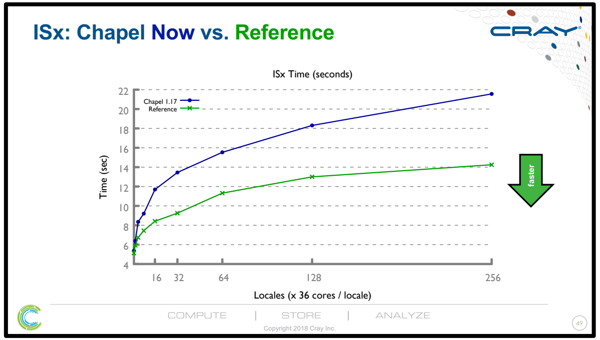


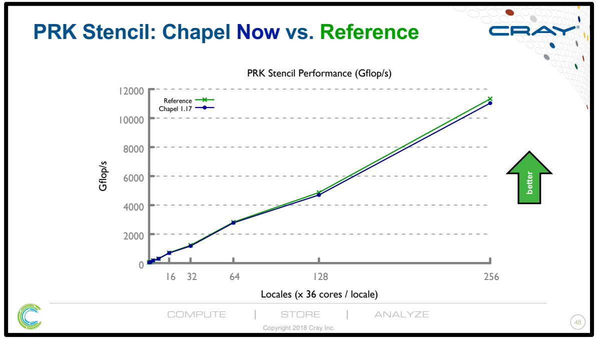

STREAM Triad

ISx

PRK Stencil

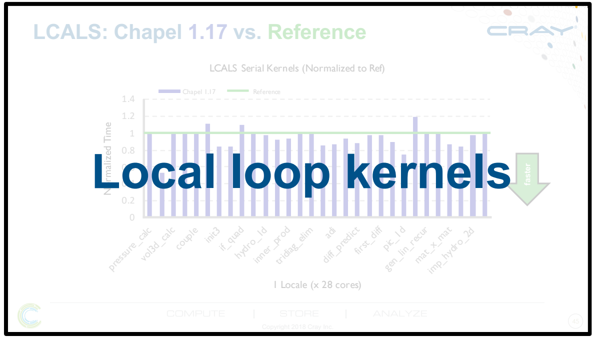



Nightly performance tickers online at:
https://chapel-lang.org/perf-nightly.html

# HPC Patterns

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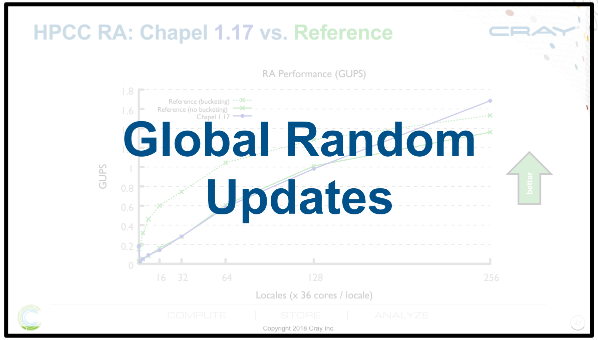


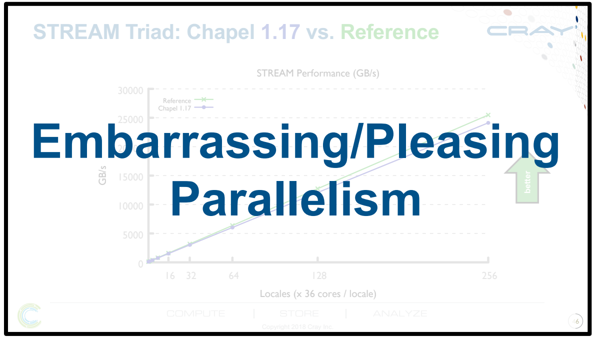


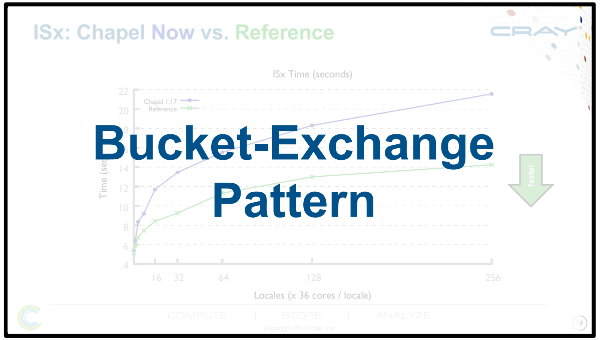


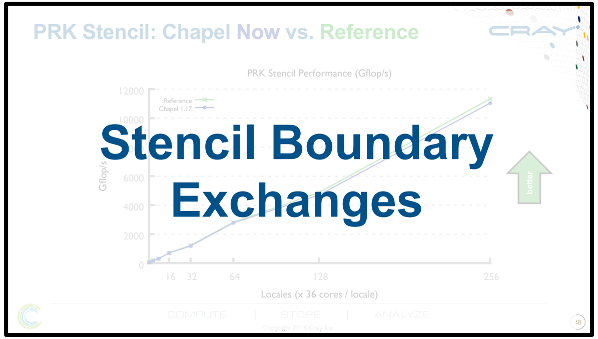


Nightly performance tickers online at:
https://chapel-lang.org/perf-nightly.html

# Array Optimizations

# Array Background

- **Arrays are a fundamental building block in HPC**
  - And a core language feature in Chapel with rich functionality
    - support for arbitrary indexing (vs. fixed 0-based or 1-based)
    - true multi-dimensional arrays
    - built-in parallel iteration
    - support for slices, rank-change, and much, much more

- **Naïve implementations of rich arrays performed poorly**
  - Over 100 times slower for LCALS benchmark
    - LCALS is a collection of simple and local loop kernels

# LCALS Serial Kernel

- Chapel code for serial pressure_calc kernel:

```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

# LCALS Serial Kernel: 1.7 Generated Code

- **Chapel code:**

```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

- **Code generated by 1.7:**

```
end3 = T22;
call_tmp94 = (ret54 != T22);
T23 = call_tmp94;
while (T23) {
  // get (bvc + i)
  ret58 = bvc;
  ret59 = (ret58)->origin;
  ret_11 = &((ret58)->blk);
  ret_x111 = *(*(ret_11) + 0);
  call_tmp95 = (i3 * ret_x111);
  call_tmp96 = (ret59 + call_tmp95);
  ret60 = (ret58)->factoredOffs;
  call_tmp97 = (call_tmp96 - ret60);
  call_tmp98 = (ret58)->data;
  call_tmp99 = (call_tmp98 + call_tmp97);

  // get (compression + i)
  ret61 = compression;
  ret62 = (ret61)->origin;
  ret_12 = &((ret61)->blk);
  ret_x112 = *(*(ret_12) + 0);
  call_tmp100 = (i3 * ret_x112);
  call_tmp101 = (ret62 + call_tmp100);
  ret63 = (ret61)->factoredOffs;
  call_tmp102 = (call_tmp101 - ret63);
  call_tmp103 = (ret61)->data;
  call_tmp104 = (call_tmp103 + call_tmp102);

  // compute cls * (*(compression + i) + 1.0)
  ret64 = *(call_tmp104);
  call_tmp105 = (ret64 + 1.0);
  call_tmp106 = (cls * call_tmp105);

  // store computation
  *(call_tmp99) = call_tmp106;

  // advance index/induction variable
  call_tmp107 = (i3 + 1);
  i3 = call_tmp107;
  call_tmp108 = (call_tmp107 != end3);
  T23 = call_tmp108;
}
```

# LCALS Serial Kernel: 1.7 Generated Code

- **Chapel code:**

```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

- **Code generated by 1.7: While-loop with != operator**

```
end3 = T22;
call_tmp94 = (ret54 != T22);
T23 = call_tmp94;
while (T23) {
  // get (bvc + i)
  ret58 = bvc;
  ret59 = (ret58)->origin;
  ret_11 = &((ret58)->blk);
  ret_x111 = *(*(ret_11) + 0);
  call_tmp95 = (i3 * ret_x111);
  call_tmp96 = (ret59 + call_tmp95);
  ret60 = (ret58)->factoredOffs;
  call_tmp97 = (call_tmp96 - ret60);
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  ret_12 = &((ret61)->blk);
  ret_x112 = *(*(ret_12) + 0);
  call_tmp100 = (i3 * ret_x112);
  call_tmp101 = (ret62 + call_tmp100);
  ret63 = (ret61)->factoredOffs;
  call_tmp102 = (call_tmp101 - ret63);
  call_tmp103 = (ret61)->data;
  call_tmp104 = (call_tmp103 + call_tmp102);

  // compute cls * (*(compression + i) + 1.0)
  ret64 = *(call_tmp104);
  call_tmp105 = (ret64 + 1.0);
  call_tmp106 = (cls * call_tmp105);

  // store computation
  *(call_tmp99) = call_tmp106;

  // advance index/induction variable
  call_tmp107 = (i3 + 1);
  i3 = call_tmp107;
  call_tmp108 = (call_tmp107 != end3);
  T23 = call_tmp108;
}
```

# LCALS Serial Kernel: 1.7 Generated Code

- **Chapel code:**

```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

- **Code generated by 1.7: Multiply by 'blk' offset**

```
end3 = T22;
call_tmp94 = (ret54 != T22);
T23 = call_tmp94;
while (T23) {
  // get (bvc + i)
  ret58 = bvc;
  ret59 = (ret58)->origin;
  ret_11 = &((ret58)->blk);
  ret_x111 = *(*(ret_11) + 0);
  call_tmp95 = (i3 * ret_x111);
  call_tmp96 = (ret59 + call_tmp95);
  ret60 = (ret58)->factoredOffs;
  call_tmp97 = (call_tmp96 - ret60);
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  // get (compression + i)
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  ret62 = (ret61)->origin;
  ret_12 = &((ret61)->blk);
  ret_x112 = *(*(ret_12) + 0);
  call_tmp100 = (i3 * ret_x112);
  call_tmp101 = (ret62 + call_tmp100);
  ret63 = (ret61)->factoredOffs;
  call_tmp102 = (call_tmp101 - ret63);
  call_tmp103 = (ret61)->data;
  call_tmp104 = (call_tmp103 + call_tmp102);

  // compute cls * (*(compression + i) + 1.0)
  ret64 = *(call_tmp104);
  call_tmp105 = (ret64 + 1.0);
  call_tmp106 = (cls * call_tmp105);

  // store computation
  *(call_tmp99) = call_tmp106;

  // advance index/induction variable
  call_tmp107 = (i3 + 1);
  i3 = call_tmp107;
  call_tmp108 = (call_tmp107 != end3);
  T23 = call_tmp108;
}
```

# LCALS Serial Kernel: 1.7 Generated Code

- **Chapel code:**

```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

- **Code generated by 1.7: 0-shift indexing**

```
end3 = T22;
call_tmp94 = (ret54 != T22);
T23 = call_tmp94;
while (T23) {
  // get (bvc + i)
  ret58 = bvc;
  ret59 = (ret58)->origin;
  ret_11 = &((ret58)->blk);
  ret_x111 = *(*(ret_11) + 0);
  call_tmp95 = (i3 * ret_x111);
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  call_tmp99 = (call_tmp98 + call_tmp97);

  // get (compression + i)
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  ret_12 = &((ret61)->blk);
  ret_x112 = *(*(ret_12) + 0);
  call_tmp100 = (i3 * ret_x112);
  call_tmp101 = (ret62 + call_tmp100);
  ret63 = (ret61)->factoredOffs;
  call_tmp102 = (call_tmp101 - ret63);
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  // compute cls * (*(compression + i) + 1.0)
  ret64 = *(call_tmp104);
  call_tmp105 = (ret64 + 1.0);
  call_tmp106 = (cls * call_tmp105);

  // store computation
  *(call_tmp99) = call_tmp106;

  // advance index/induction variable
  call_tmp107 = (i3 + 1);
  i3 = call_tmp107;
  call_tmp108 = (call_tmp107 != end3);
  T23 = call_tmp108;
}
```

# LCALS Serial Kernel: 1.7 Generated Code

- **Chapel code:**

```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

- **Code generated by 1.7: Extra dereferences**

```
end3 = T22;
call_tmp94 = (ret54 != T22);
T23 = call_tmp94;
while (T23) {
  // get (bvc + i)
  ret58 = bvc;
  ret59 = (ret58)->origin;
  ret_11 = &((ret58)->blk);
  ret_x111 = *(*(ret_11) + 0);
  call_tmp95 = (i3 * ret_x111);
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  // get (compression + i)
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  ret_x112 = *(*(ret_12) + 0);
  call_tmp100 = (i3 * ret_x112);
  call_tmp101 = (ret62 + call_tmp100);
  ret63 = (ret61)->factoredOffs;
  call_tmp102 = (call_tmp101 - ret63);
  call_tmp103 = (ret61)->data;
  call_tmp104 = (call_tmp103 + call_tmp102);

  // compute cls * (*(compression + i) + 1.0)
  ret64 = *(call_tmp104);
  call_tmp105 = (ret64 + 1.0);
  call_tmp106 = (cls * call_tmp105);

  // store computation
  *(call_tmp99) = call_tmp106;

  // advance index/induction variable
  call_tmp107 = (i3 + 1);
  i3 = call_tmp107;
  call_tmp108 = (call_tmp107 != end3);
  T23 = call_tmp108;
}
```

# LCALS Serial Kernel: 1.7 Generated Code

- **Chapel code:**

```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

- **Code generated by 1.7:**

```
end3 = T22;
call_tmp94 = (ret54 != T22);
T23 = call_tmp94;
while (T23) {
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  ret64 = *(call_tmp104);
  call_tmp105 = (ret64 + 1.0);
  call_tmp106 = (cls * call_tmp105);

  // store computation
  *(call_tmp99) = call_tmp106;

  // advance index/induction variable
  call_tmp107 = (i3 + 1);
  i3 = call_tmp107;
  call_tmp108 = (call_tmp107 != end3);
  T23 = call_tmp108;
}
```

# Array Optimizations

- **Implemented a "shifted data" optimization**
  - Eliminates overhead of arbitrary indexing
- **Implemented loop-invariant code motion**
  - Eliminates array meta-data references in loop bodies
- **Eliminated a multiply in indexing operations**
  - (Required for outermost dimensions of multi-dimensional arrays)
- **Dramatically improved generated code for loops**

# LCALS Serial Kernel: 1.7 Generated Code

- **Chapel code:**

```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

- **Code generated by 1.7:**

```
end3 = T22;
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  // compute cls * (*(compression + i) + 1.0)
  ret64 = *(call_tmp104);
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  call_tmp106 = (cls * call_tmp105);

  // store computation
  *(call_tmp99) = call_tmp106;

  // advance index/induction variable
  call_tmp107 = (i3 + 1);
  i3 = call_tmp107;
  call_tmp108 = (call_tmp107 != end3);
  T23 = call_tmp108;
}
```

# LCALS Serial Kernel: 1.17 Generated Code

- **Chapel code:**

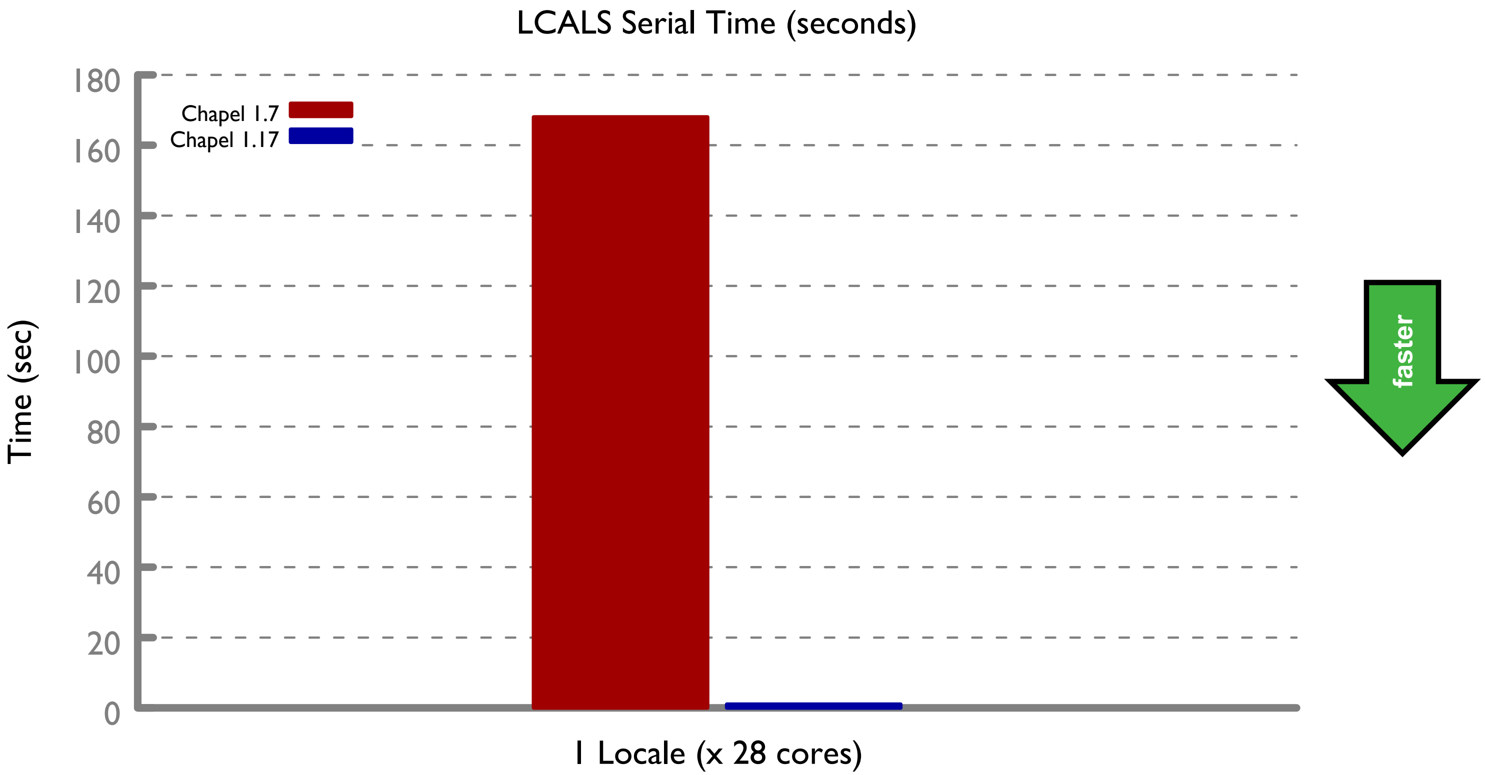
```
for i in 0..#len do
  bvc[i] = cls * (compression[i] + 1.0);
```

- **Code generated by 1.17:**

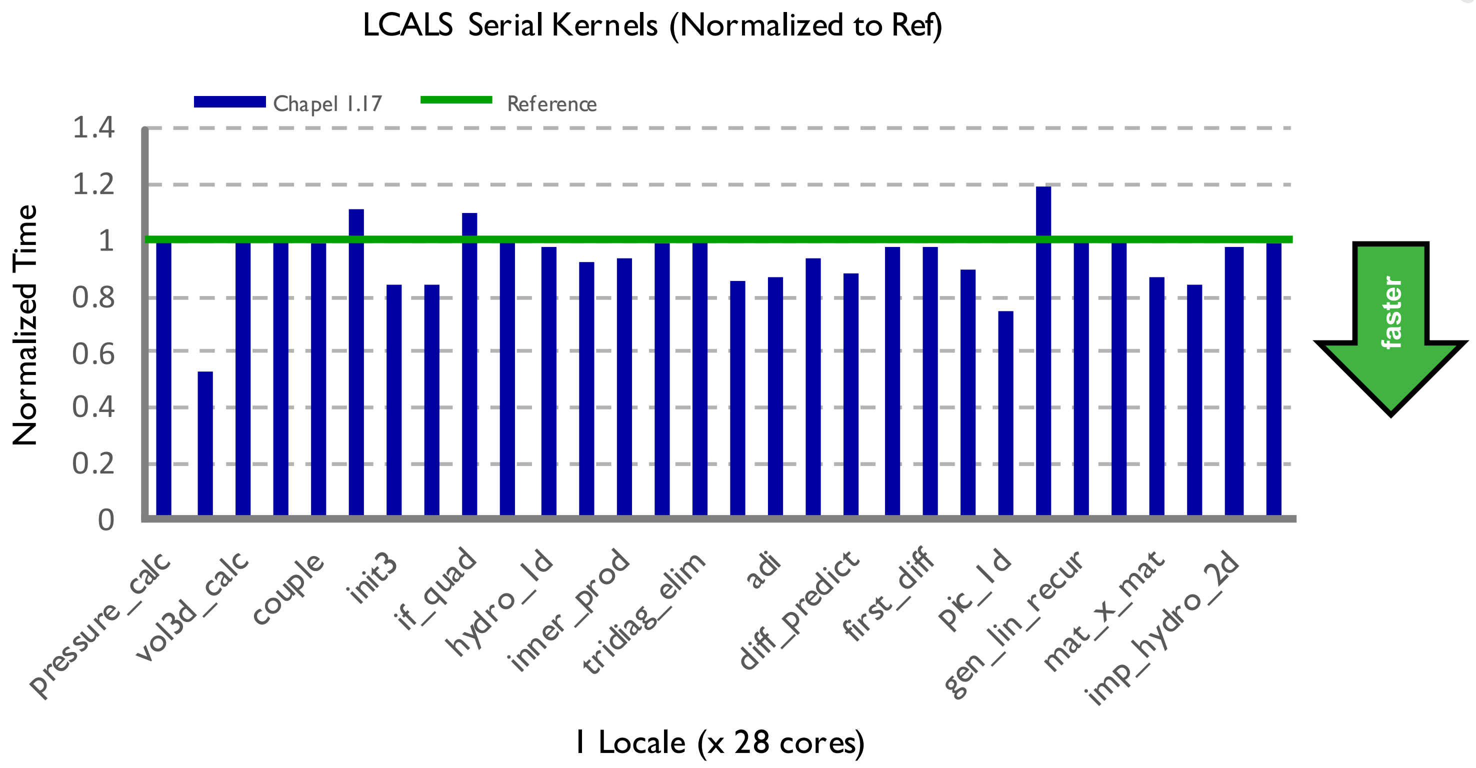
```
bvc_p = (bvc_inst)->shiftedData;                         // Shifted pointer (hoisted)
compression_p = (compression_inst)->shiftedData;

for (i = 0; i <= len-1; i += 1) {                        // Normalized C-for loop (<=)
  bvc_p_i = (bvc_p + i);                                 // Direct index offset (no mult)
  compression_p_i = (compression_p + i);
  *(bvc_p_i) = cls * ((*compression_p_i) + 1.0);
}
```

# LCALS Serial Kernel: Chapel Then vs. Now



# LCALS Serial Kernels: Chapel Now vs. Ref



# Runtime Optimizations

# Runtime Background

- **Chapel's runtime responsible for low-level operations:**
  - Memory allocation
  - Task spawning
  - Topology discovery
  - Communication
- **Default runtime in 1.7 was functional/portable, but slow**
  - Some faster layers available, but were highly experimental

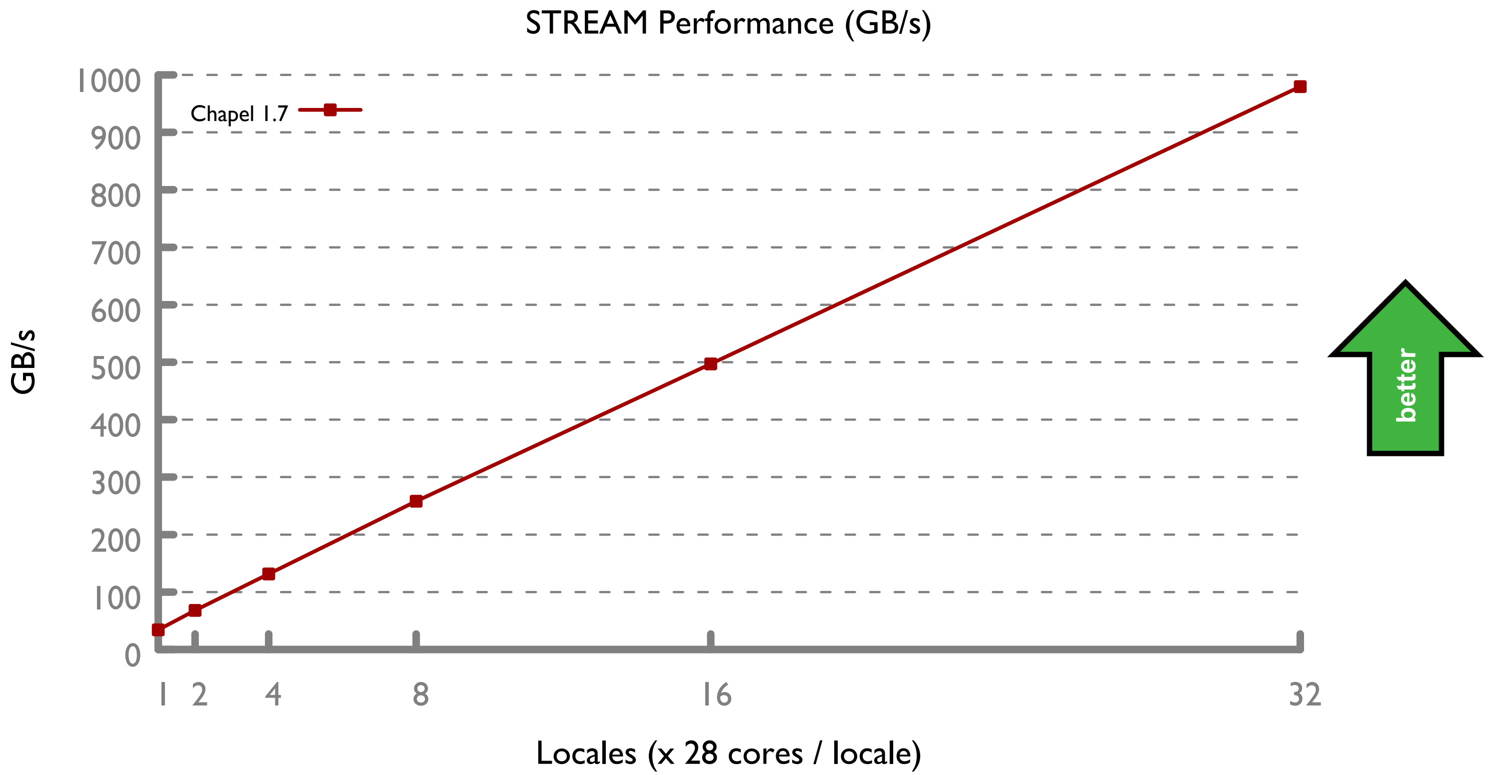
# Chapel Runtime: Then

- **Memory allocations satisfied by the system allocator**
  - Most system allocations have poor parallel allocation performance
- **Chapel tasks were mapped directly to system pthreads**
  - Incurs high task spawning and task switching times
  - No regard for NUMA affinity between consecutive parallel loops
- **Communication done with GASNet over MPI substrate**
  - Did not utilize underlying network capabilities (RDMA, AMO, etc.)

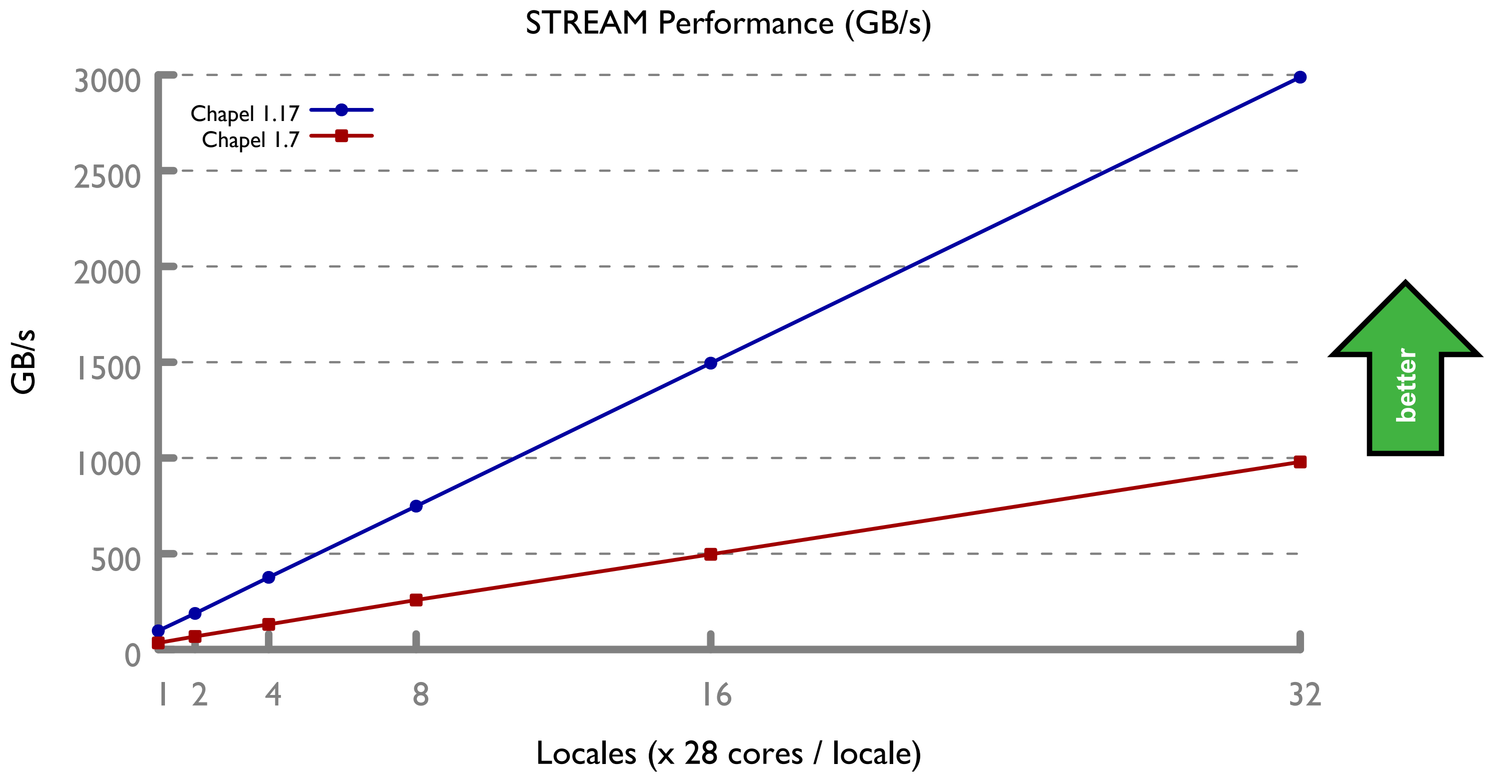
# Chapel Runtime: Now

- **Memory allocations satisfied by concurrent allocator**
  - Parallel and highly scalable allocator built on top of jemalloc
- **Tasks are mapped to lightweight user-level qthreads**
  - Extremely fast task creation and spawning in user-space
  - Affinity awareness via hwloc (consecutive foralls run same tasks)
- **Communication on Crays mapped to uGNI**
  - Optimized RDMA operations (gets, puts, AMs, network atomics)
  - Scalability performance with limited software overhead

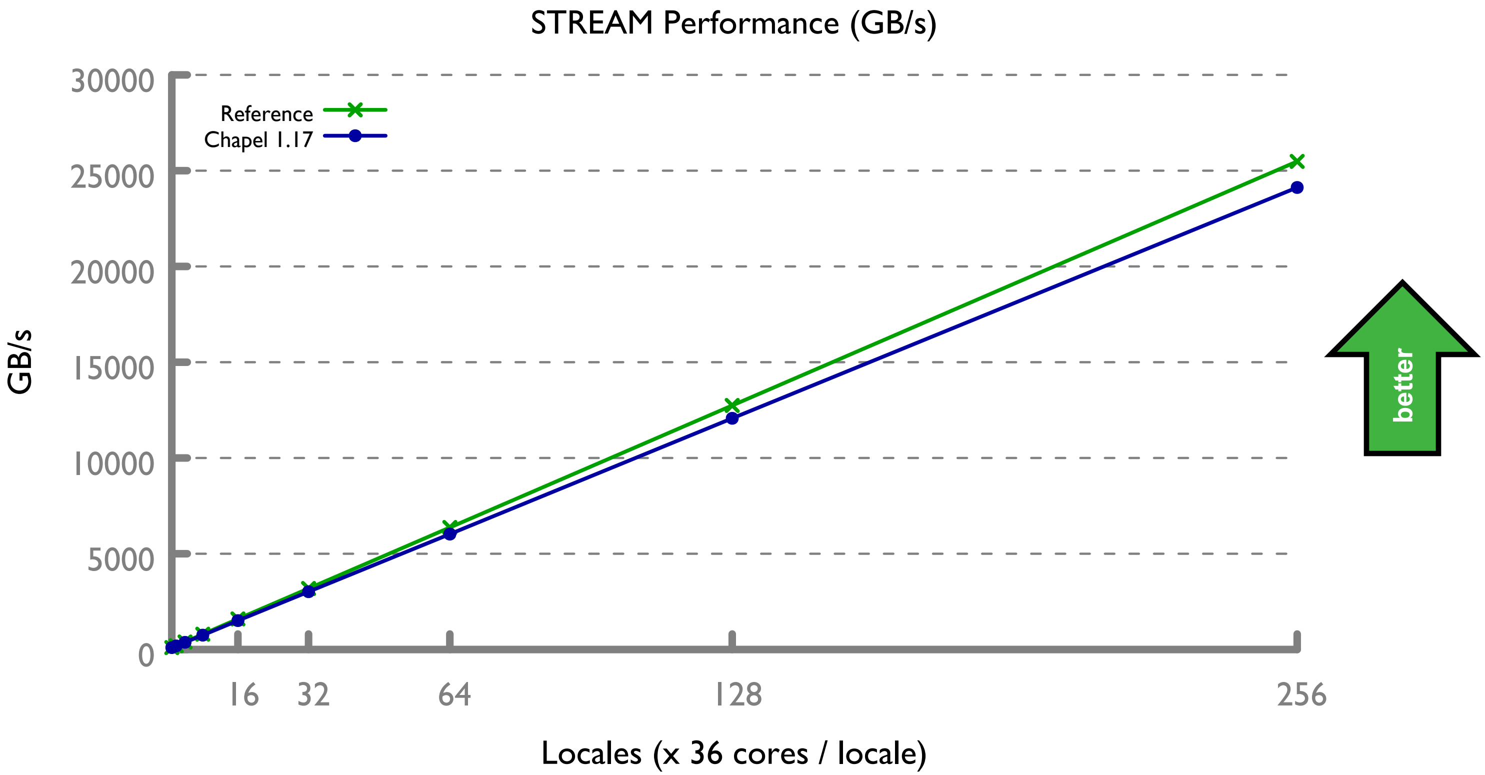
# HPCC STREAM Triad: Chapel Then



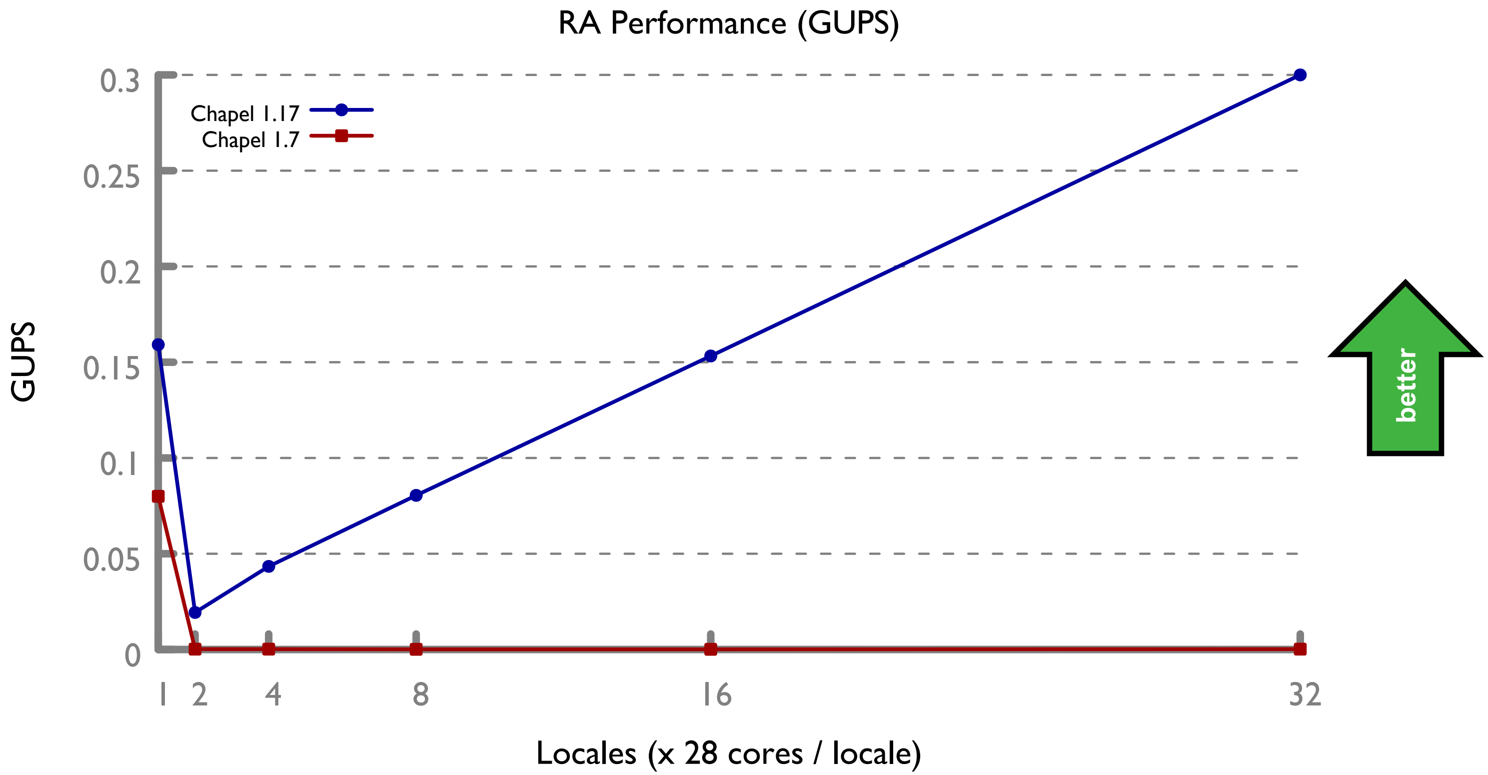
# HPCC STREAM Triad: Chapel Then vs. Now



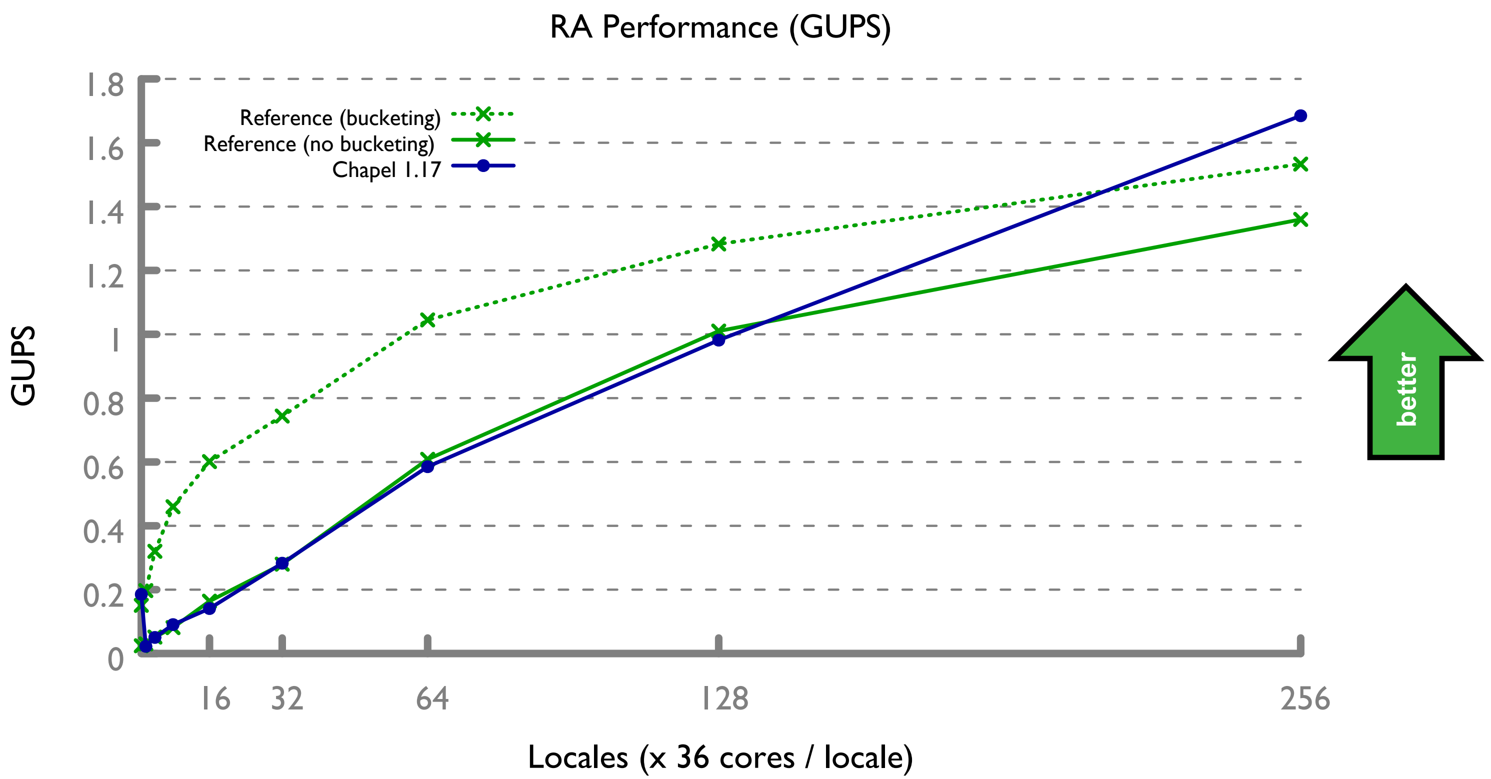
# HPCC STREAM Triad: Chapel Now vs. Ref



# HPCC RA: Chapel Then vs. Now



# HPCC RA: Chapel Now vs. Ref



# Communication Reductions

# Communication Background

- **Chapel compiler is responsible for communication**
  - Must insert runtime calls for “wide” (possibly remote) data
  - Call includes conditional for short-circuit or actual network comm
    - conditional branch and function call thwart backend optimizations

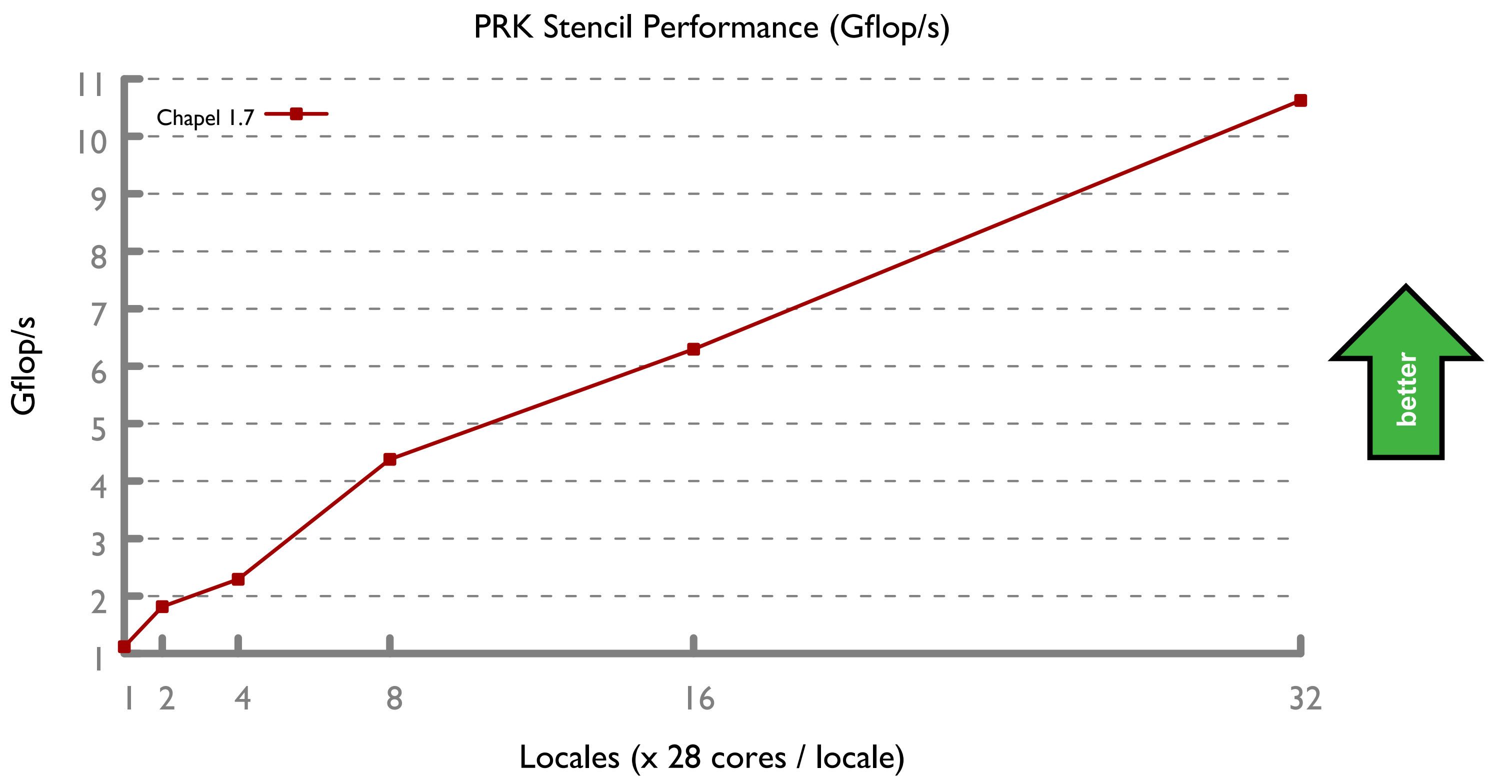
# Chapel Communication: Then

- **Everything was initially widened**
  - And then attempted to narrow some calls
- **Array assignments were performed element at a time**
  - With meta-data access, resulted in ~5*#elements comm events
- **In general, little done to optimization communication**

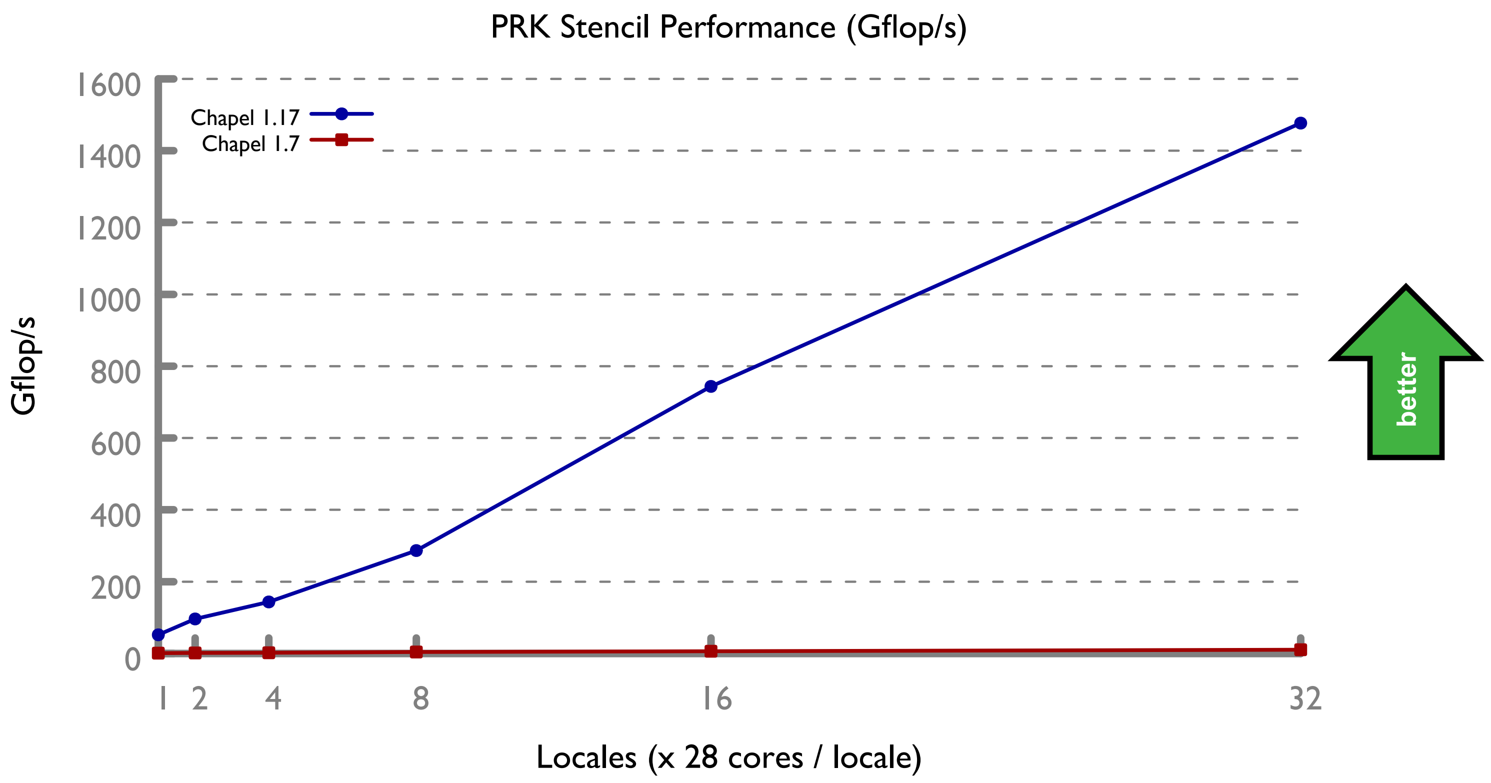
# Chapel Communication: Now

- **Only widen what we can't prove is local**
  - Dramatic decrease in locality checks required at runtime
- **Array assignments are performed as 1 operation**
  - With meta-data hoisted, results in ~3 comm events
    - 2 small comms for meta-data, one large comm for all elements
- **Many other communication optimizations implemented**
  - Improved remote-value-forwarding, new distributions, LICM, fast-on optimization, and much more

# PRK Stencil: Chapel Then



# PRK Stencil: Chapel Then vs. Now



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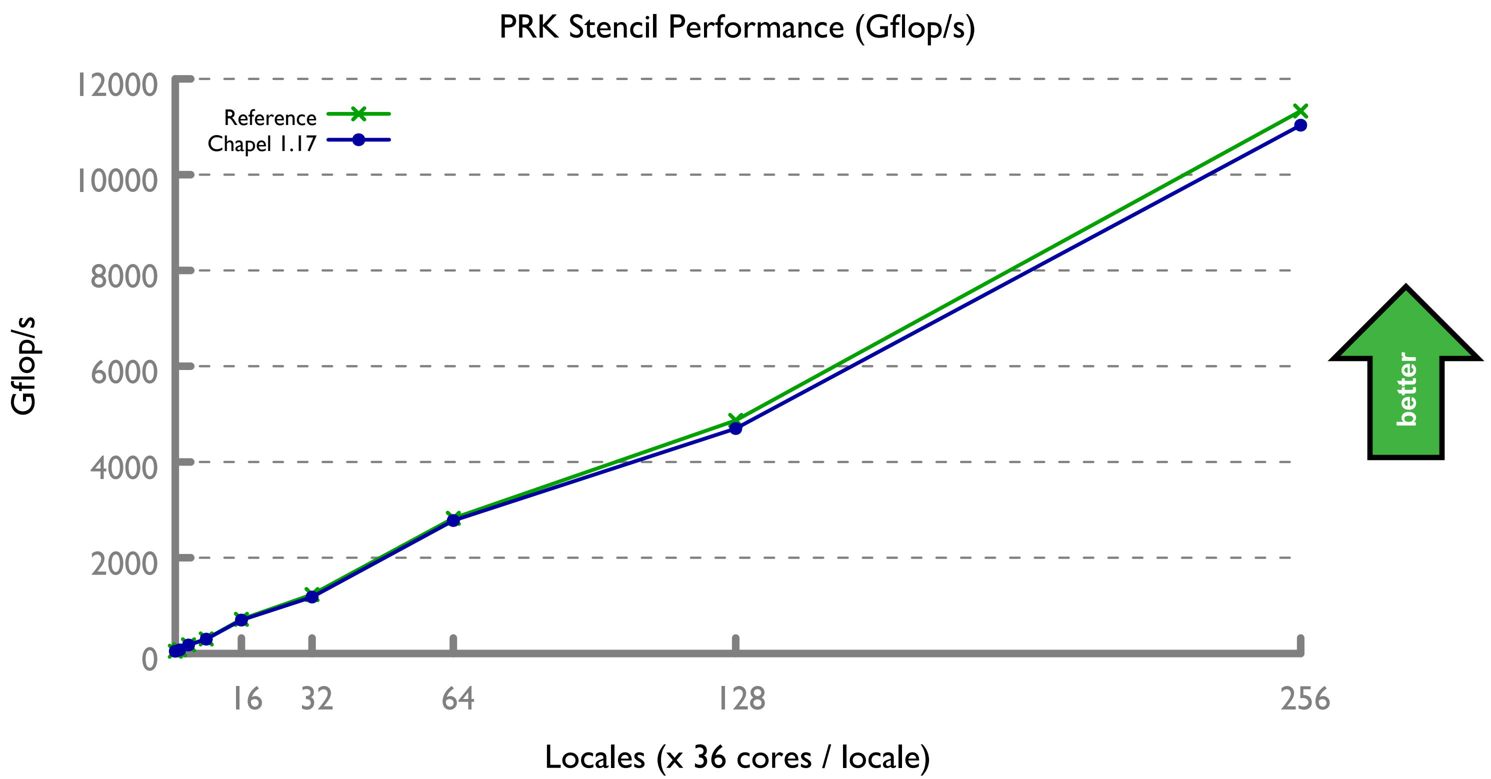
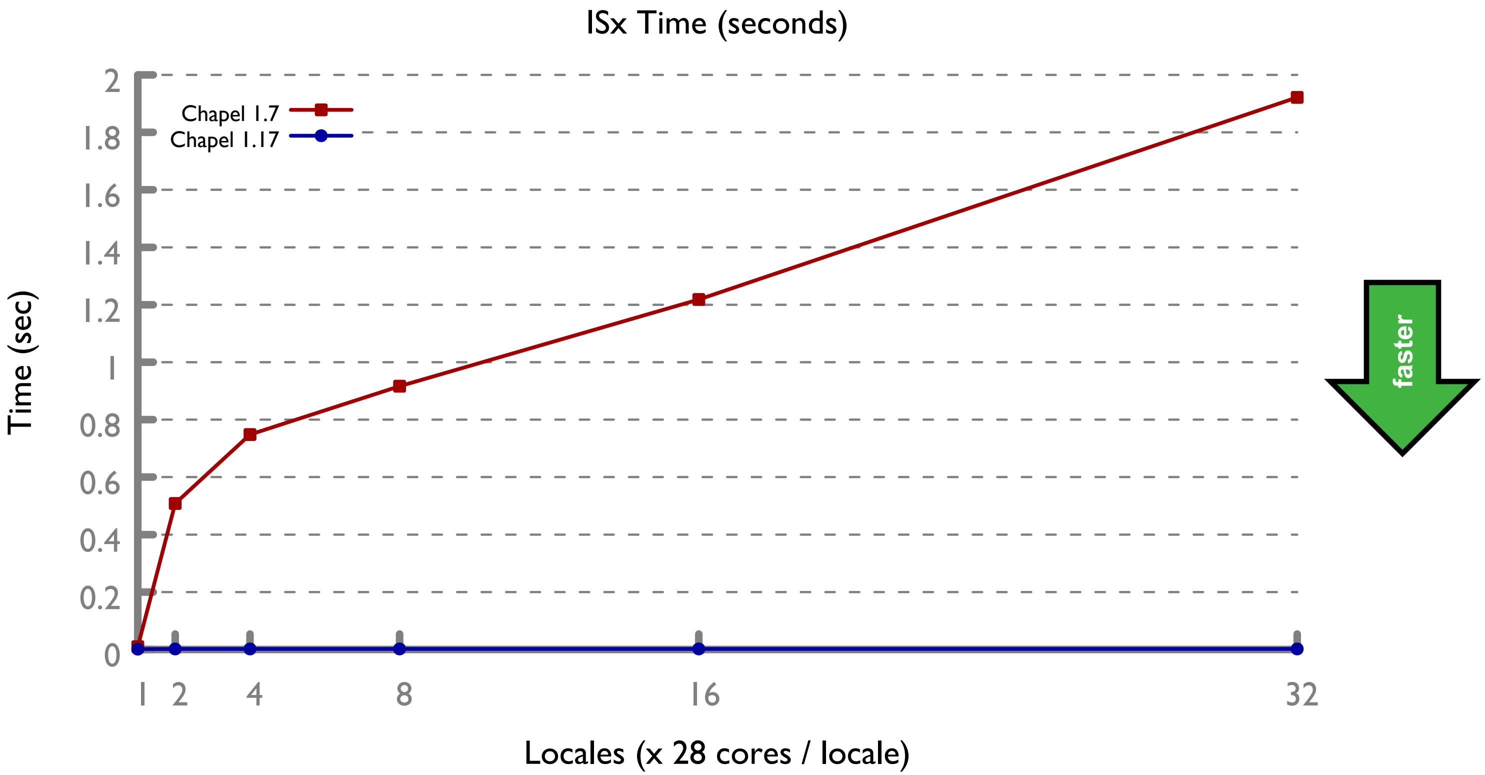
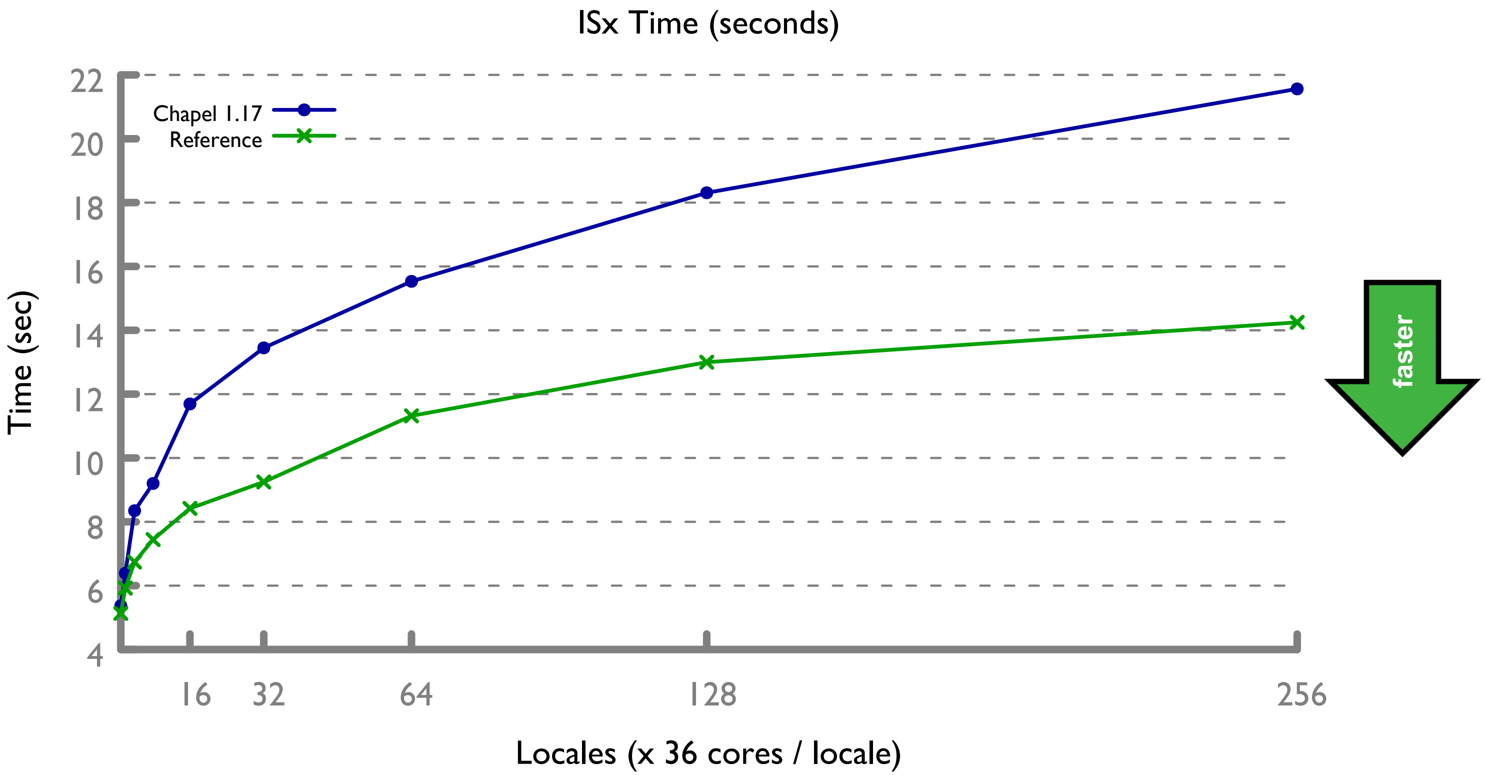


# ISx: Chapel Then vs. Now



# ISx: Chapel Now vs. Ref



# Performance Summary

# Performance Summary

## Array Optimizations:

- shifted data optimization (eliminates arbitrary indexing overhead)
- loop-invariant code motion (eliminates meta-data overhead)
- eliminated multiply in indexing for 1D (and innermost dim of 2D+) arrays

## Runtime Improvements:

- scalable parallel memory allocator
- tasks mapped to affinity aware user-level threads
- native/optimized comm with RDMA and limited software overhead

## Optimized Communication:

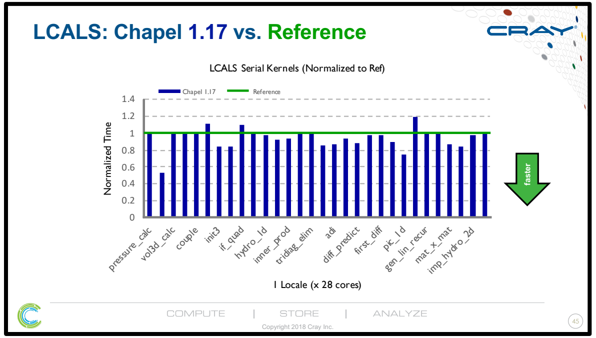
- compiler locality analysis improvements
- bulk array assignments
- remote-value-forwarding, new distributions, fast-ons, …

# Performance Summary

- **Possible to write Chapel code that competes with MPI**
  - And other established HPC technologies (OpenMP, SHMEM, etc.)
- **Still possible to fall off a performance cliff**
  - In some cases due to lack of user-education
  - In other cases, we still have optimizations to implement
- **We believe Chapel has demonstrated it can perform**
  - Let us know if you see otherwise

# Performance Summary

LCALS

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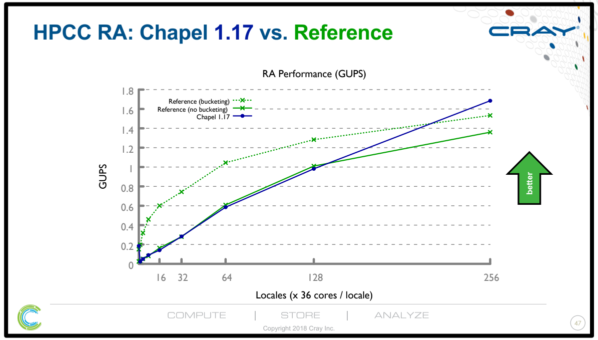
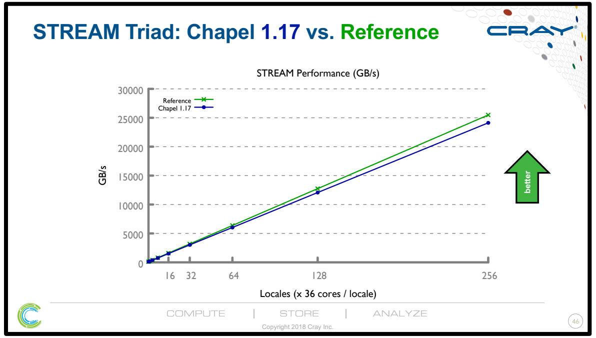
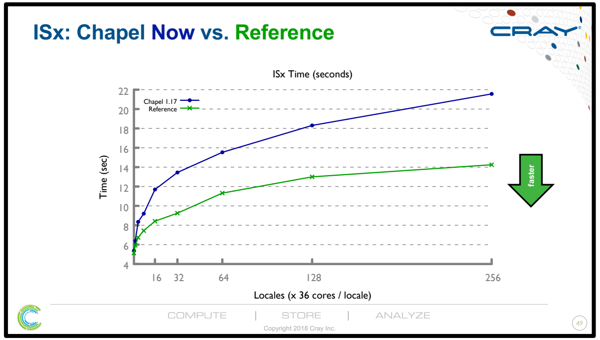


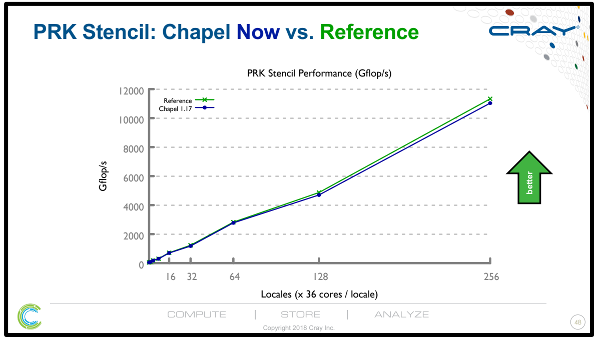

STREAM Triad




ISx




PRK Stencil




Nightly performance tickers online at:
https://chapel-lang.org/perf-nightly.html

# Crossing the Stream of Adoption

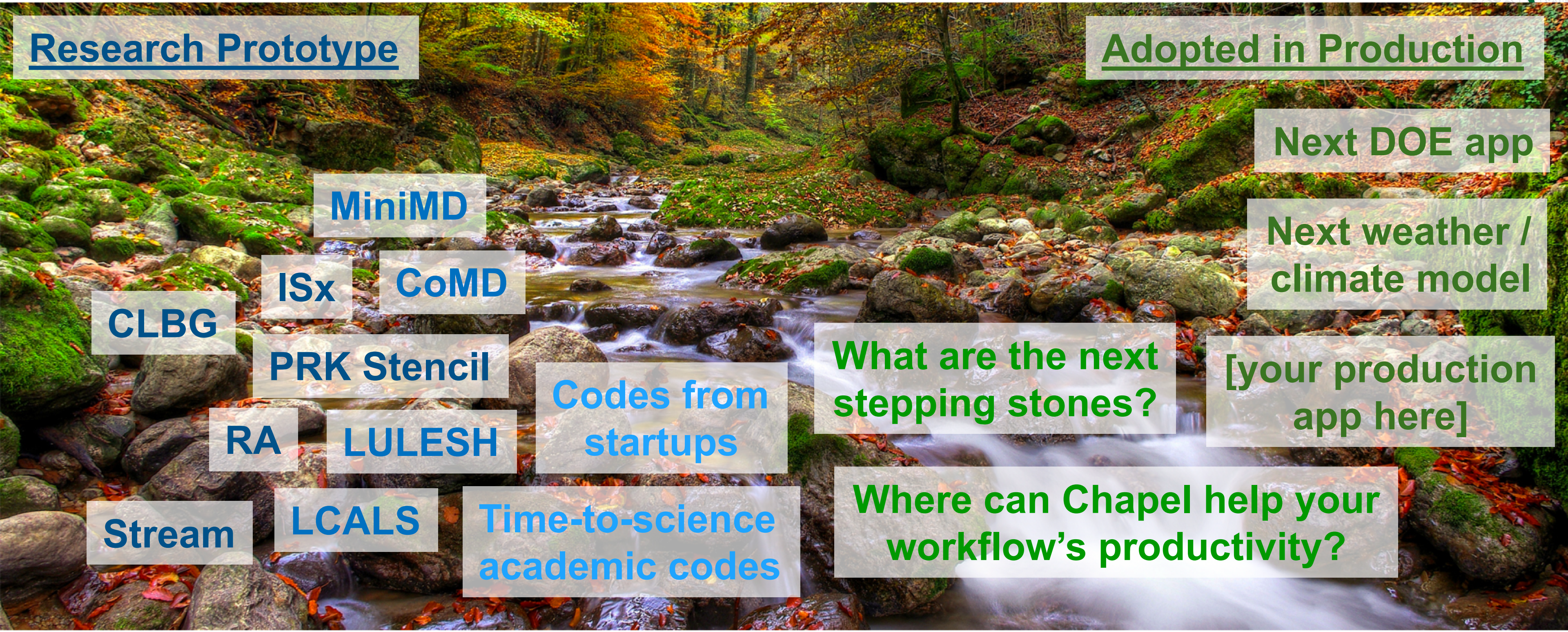




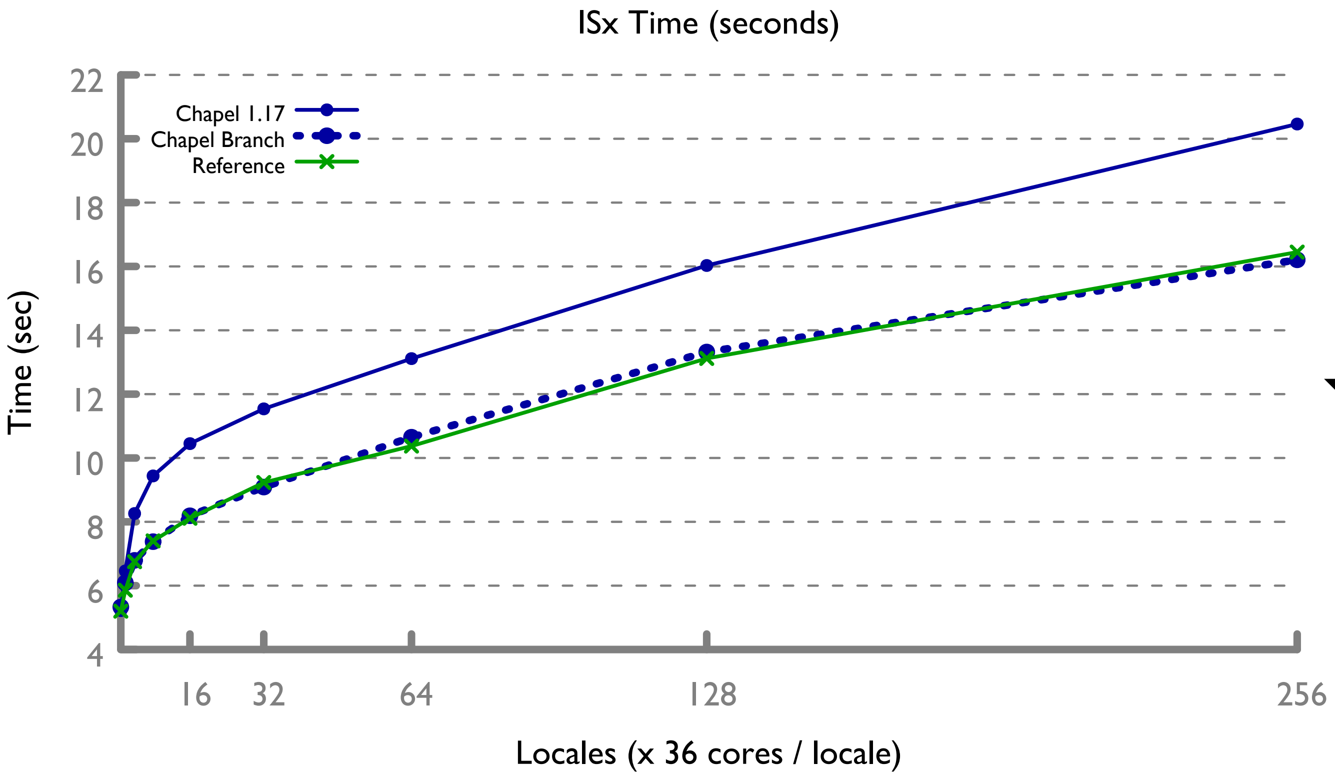

image credit: http://feelgrafix.com/813578-free-stream-wallpaper.html

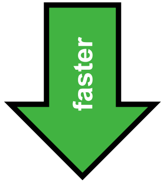
# Next Steps

# Next Steps

- **Improve ISx performance**
  - Achieve performance parity with reference version
    - (Next slide contains results from prototype branch)
- **Perform scalability testing at higher locale counts**
  - Have done preliminary testing on 1,024 locales on NERSC Edison
    - PRK Stencil ~10% off from reference at 1,024 nodes
    - Plan to address with more scalable tree-based remote task-spawn
- **Focus optimization efforts on user applications**

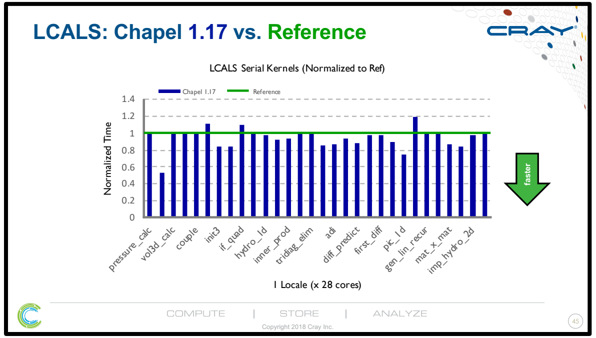
# ISx: Chapel Now vs. Train Ride Branch vs. Ref



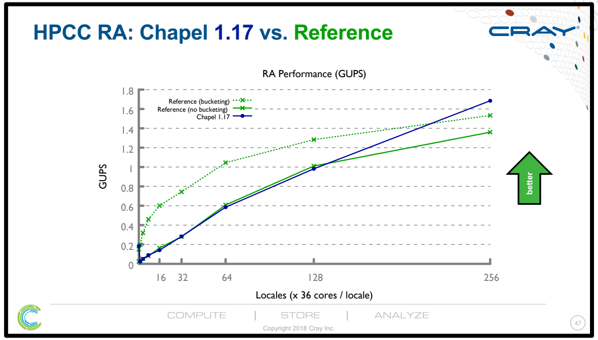
# Questions?

# Performance Summary




LCALS

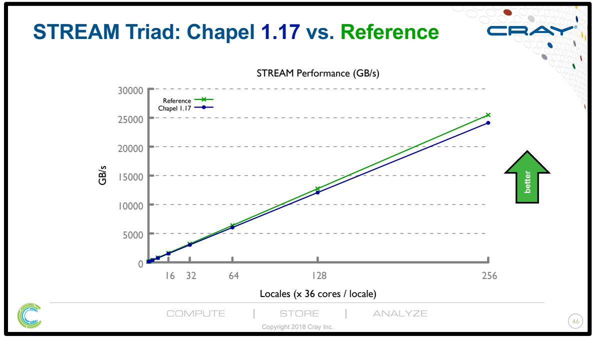
HPCC RA

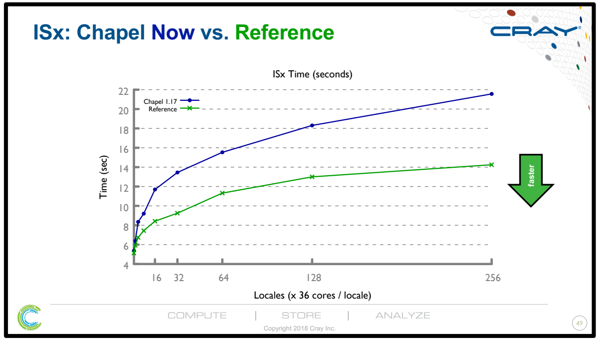


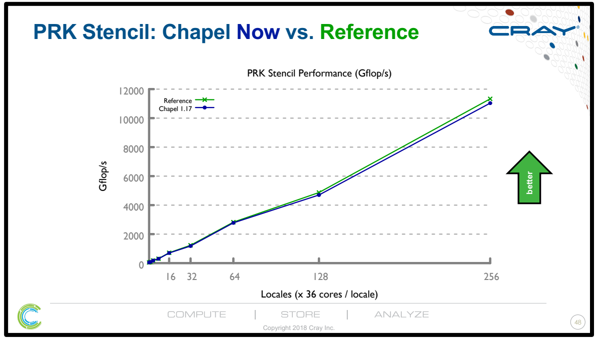

STREAM Triad

ISx

PRK Stencil

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