RECENT PERFORMANCE ADVANCES IN CHAPEL AND ARKOUDA

Brad Chamberlain, Elliot Ronaghan, Engin Kayraklioglu

OpenSHMEM 2021 keynote
September 16, 2021

OR: MULTIRESOLUTION SUPPORT FOR AGGREGATED COMMUNICATION IN CHAPEL

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Hewlett Packard Enterprise

OR: CHAPEL! AGGREGATION!! LET'S GO!!!

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WHAT IS CHAPEL?

Chapel: A modern parallel programming language

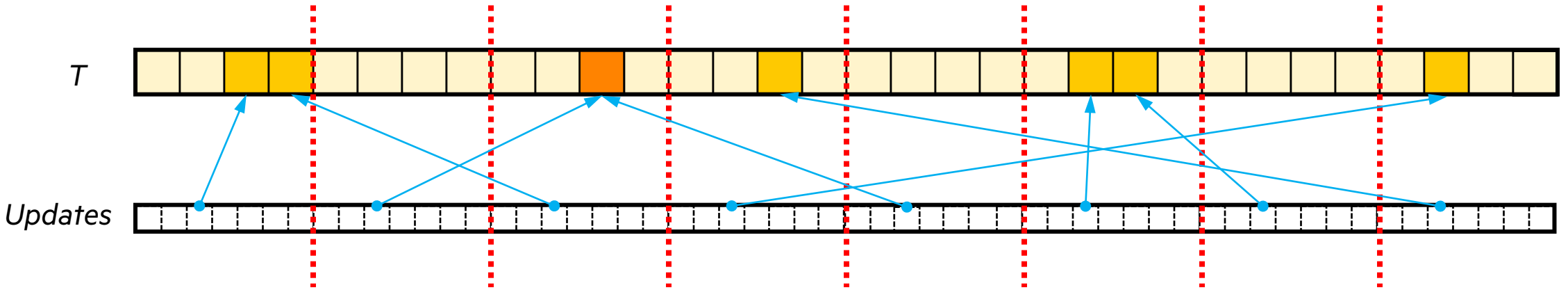
- portable & scalable
- open-source & collaborative

Goals:

- Support general parallel programming
- Make parallel programming at scale far more productive

HPCC RANDOM ACCESS (RA)

Data Structure: distributed table



Computation: in parallel, update random table elements with random values

Declarations: distributed table and index space of updates in Chapel:

```
var T: [newBlockDom(0..<tableSize)] int;
const Updates = newBlockDom(0..<numUpdates);
```

HPCC RA: MPI KERNEL

```
/* Perform updates to main table.  The scalar equivalent is:
 *
 *   for (i=0; i<NUPDATE; i++) {
 *     Ran = (Ran << 1) ^ (((s64Int) Ran < 0) ? POLY : 0);
 *     Table[Ran & (TABSIZE-1)] ^= Ran;
 *   }
 */

MPI_Irecv(&LocalRecvBuffer, localBufferSize, tparams.dtype64,
          MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &inreq);
 while (i < SendCnt) {
   /* receive messages */
   do {
     MPI_Test(&inreq, &have_done, &status);
     if (have_done) {
       if (status.MPI_TAG == UPDATE_TAG) {
         MPI_Get_count(&status, tparams.dtype64, &recvUpdates);
         bufferBase = 0;
         for (j=0; j < recvUpdates; j ++) {
           inmsg = LocalRecvBuffer[bufferBase+j];
           LocalOffset = (inmsg & (tparams.TableSize - 1)) -
                         tparams.GlobalStartMyProc;
           HPCC_Table[LocalOffset] ^= inmsg;
         }
       } else if (status.MPI_TAG == FINISHED_TAG) {
         NumberReceiving--;
       } else
         MPI_Abort( MPI_COMM_WORLD, -1 );
       MPI_Irecv(&LocalRecvBuffer, localBufferSize, tparams.dtype64,
                 MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &inreq);
     }
   } while (have_done && NumberReceiving > 0);
   if (pendingUpdates < maxPendingUpdates) {
     Ran = (Ran << 1) ^ ((s64Int) Ran < ZERO64B ? POLY : ZERO64B);
     GlobalOffset = Ran & (tparams.TableSize-1);
     if ( GlobalOffset < tparams.Top)
       WhichPe = ( GlobalOffset / (tparams.MinLocalTableSize + 1) );
     else
       WhichPe = ( (GlobalOffset - tparams.Remainder) /
                 tparams.MinLocalTableSize );
     if (WhichPe == tparams.MyProc) {
       LocalOffset = (Ran & (tparams.TableSize - 1)) -
                     tparams.GlobalStartMyProc;
       HPCC_Table[LocalOffset] ^= Ran;
     } else {
       HPCC_InsertUpdate(Ran, WhichPe, Buckets);
       pendingUpdates++;
     }
     i++;
   }
   else {
     MPI_Test(&outreq, &have_done, MPI_STATUS_IGNORE);
     if (have_done) {
       outreq = MPI_REQUEST_NULL;
       pe = HPCC_GetUpdates(Buckets, LocalSendBuffer, localBufferSize,
                            &peUpdates);
       MPI_Isend(&LocalSendBuffer, peUpdates, tparams.dtype64, (int)pe,
                 UPDATE_TAG, MPI_COMM_WORLD, &outreq);
       pendingUpdates -= peUpdates;
     }
   }
 }
/* send remaining updates in buckets */
while (pendingUpdates > 0) {
   /* receive messages */
   do {
     MPI_Test(&inreq, &have_done, &status);
     if (have_done) {
       if (status.MPI_TAG == UPDATE_TAG) {
         MPI_Get_count(&status, tparams.dtype64, &recvUpdates);
         bufferBase = 0;
         for (j=0; j < recvUpdates; j ++) {
           inmsg = LocalRecvBuffer[bufferBase+j];
           LocalOffset = (inmsg & (tparams.TableSize - 1)) -
                         tparams.GlobalStartMyProc;
           HPCC_Table[LocalOffset] ^= inmsg;
         }
       } else if (status.MPI_TAG == FINISHED_TAG) {
         /* we got a done message.  Thanks for playing... */
         NumberReceiving--;
       } else {
         MPI_Abort( MPI_COMM_WORLD, -1 );
       }
       MPI_Irecv(&LocalRecvBuffer, localBufferSize, tparams.dtype64,
                 MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &inreq);
     }
   } while (have_done && NumberReceiving > 0);
     MPI_Test(&outreq, &have_done, MPI_STATUS_IGNORE);
     if (have_done) {
       outreq = MPI_REQUEST_NULL;
       pe = HPCC_GetUpdates(Buckets, LocalSendBuffer, localBufferSize,
                            &peUpdates);
       MPI_Isend(&LocalSendBuffer, peUpdates, tparams.dtype64, (int)pe,
                 UPDATE_TAG, MPI_COMM_WORLD, &outreq);
       pendingUpdates -= peUpdates;
     }
   }
 }
/* send our done messages */
for (proc_count = 0 ; proc_count < tparams.NumProcs ; ++proc_count) {
   if (proc_count == tparams.MyProc) { tparams.finish_req[tparams.MyProc] =
                                       MPI_REQUEST_NULL; continue; }
   /* send garbage - who cares, no one will look at it */
   MPI_Isend(&Ran, 0, tparams.dtype64, proc_count, FINISHED_TAG,
             MPI_COMM_WORLD, tparams.finish_req + proc_count);
 }
/* Finish everyone else up... */
while (NumberReceiving > 0) {
   MPI_Wait(&inreq, &status);
   if (status.MPI_TAG == UPDATE_TAG) {
     MPI_Get_count(&status, tparams.dtype64, &recvUpdates);
     bufferBase = 0;
     for (j=0; j < recvUpdates; j ++) {
       inmsg = LocalRecvBuffer[bufferBase+j];
       LocalOffset = (inmsg & (tparams.TableSize - 1)) -
                     tparams.GlobalStartMyProc;
       HPCC_Table[LocalOffset] ^= inmsg;
     }
   } else if (status.MPI_TAG == FINISHED_TAG) {
     /* we got a done message.  Thanks for playing... */
     NumberReceiving--;
   } else {
     MPI_Abort( MPI_COMM_WORLD, -1 );
   }
   MPI_Irecv(&LocalRecvBuffer, localBufferSize, tparams.dtype64,
             MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &inreq);
 }

MPI_Waitall( tparams.NumProcs, tparams.finish_req, tparams.finish_statuses);
```

HPCC RA: CHAPEL VS. MPI KERNEL COMMENT

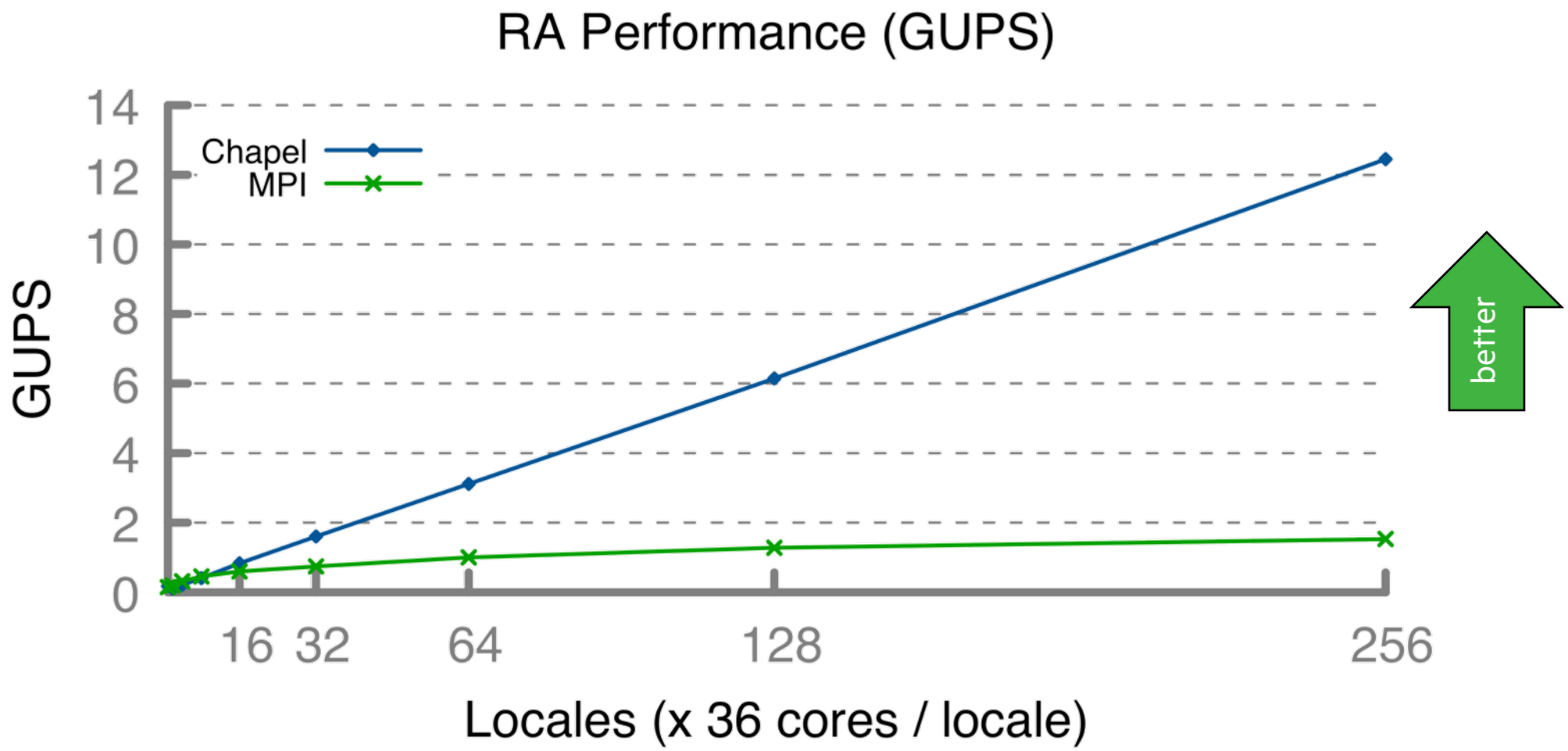
Chapel Kernel

```
forall (_, r) in zip(Updates, RAStream()) do
  T[r & indexMask].xor(r);
```

MPI Comment

```
/* Perform updates to main table. The scalar equivalent is:
 *
 *      for (i=0; i<NUPDATE; i++) {
 *        Ran = (Ran << 1) ^ (((s64Int) Ran < 0) ? POLY : 0);
 *        Table[Ran & (TABSIZE-1)] ^= Ran;
 *      }
 */
```

HPCC RA: CHAPEL VS. C+MPI



HPCC RA IN CHAPEL: NAÏVE IMPLEMENTATION

Chapel Kernel

```
forall (_, r) in zip(Updates, RAStream()) do
  T[r & indexMask].xor(r);
```

Gets lowered roughly to…

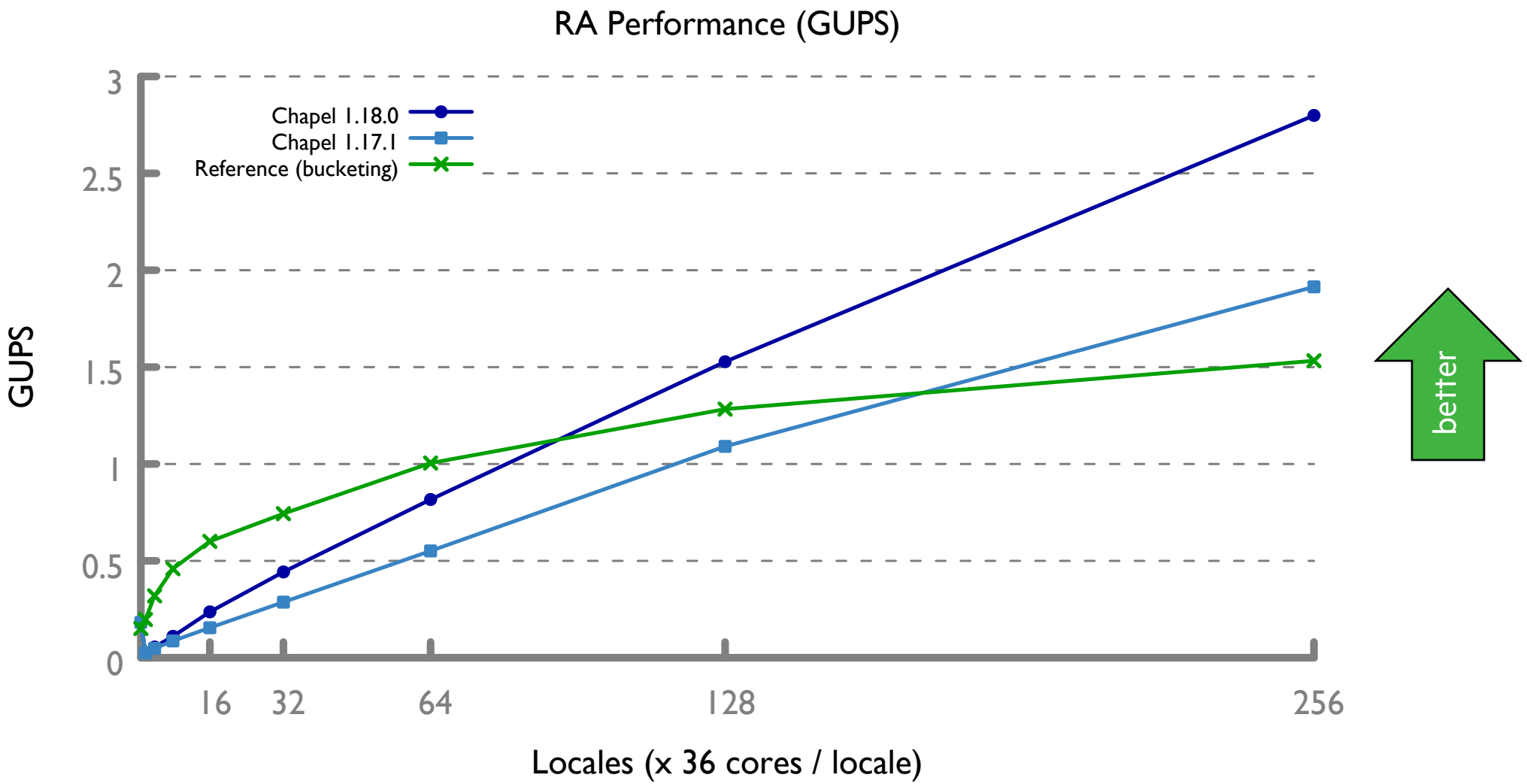
```
coforall loc in Updates.targetLocales do
  on loc do
    coforall tid in 1..here.numPUs() do
      for idx in myInds(loc, tid, …) do
        T[idx & indexMask].xor(idx);
}
```

A concurrent loop over the compute nodes

A nested concurrent loop over each node's cores

A serial loop to compute each task's chunk of updates

HPCC RA: NAÏVE CHAPEL VS. C+MPI (SEPTEMBER 2018)



UNORDERED OPERATION OPTIMIZATION

Chapel Kernel

```
forall (_, r) in zip(Updates, RAStream()) do
  T[r & indexMask].xor(r);
```

```
coforall loc in Updates.targetLocales do
  on loc do
    coforall tid in 1..here.numPUs() do
      for idx in myInds(loc, tid, …) do
        T[idx & indexMask].xor(idx);
}
```

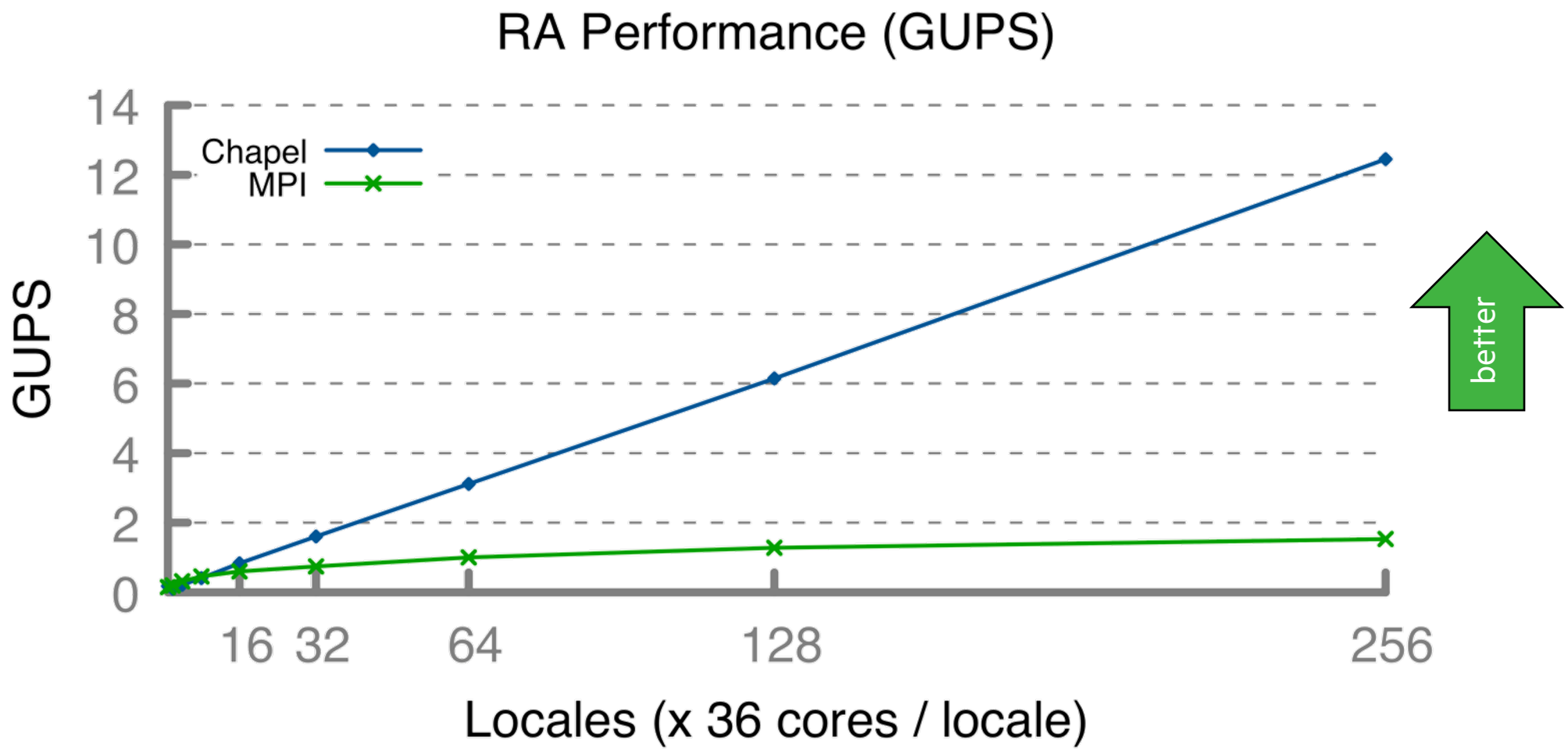
But, for a parallel loop with no data dependencies, why perform these high-latency operations serially?

So, our compiler rewrites the inner loop to perform the ops asynchronously

```
for idx in myInds(loc, tid, …) do
  T[idx & indexMask].unorderedXor(idx);
unorderedFence();
```

- Implemented by Michael Ferguson and Elliot Ronaghan, 2019

HPCC RA: CHAPEL VS. C+MPI (TODAY)



HPCC RA: CHAPEL VS. C+MPI

Chapel Kernel

```
forall (_, r) in zip(Updates, RAStream()) do
  T[r & indexMask].xor(r);
```

Now, think about what it would take for a compiler to optimize the C+MPI code…

…or for a user to target the Cray XC's network atomics manually (and portably?)

OUTLINE

I. Chapel by Example: HPCC RA

II. Chapel Motivation & Context

III. “Low-level” Chapel Features

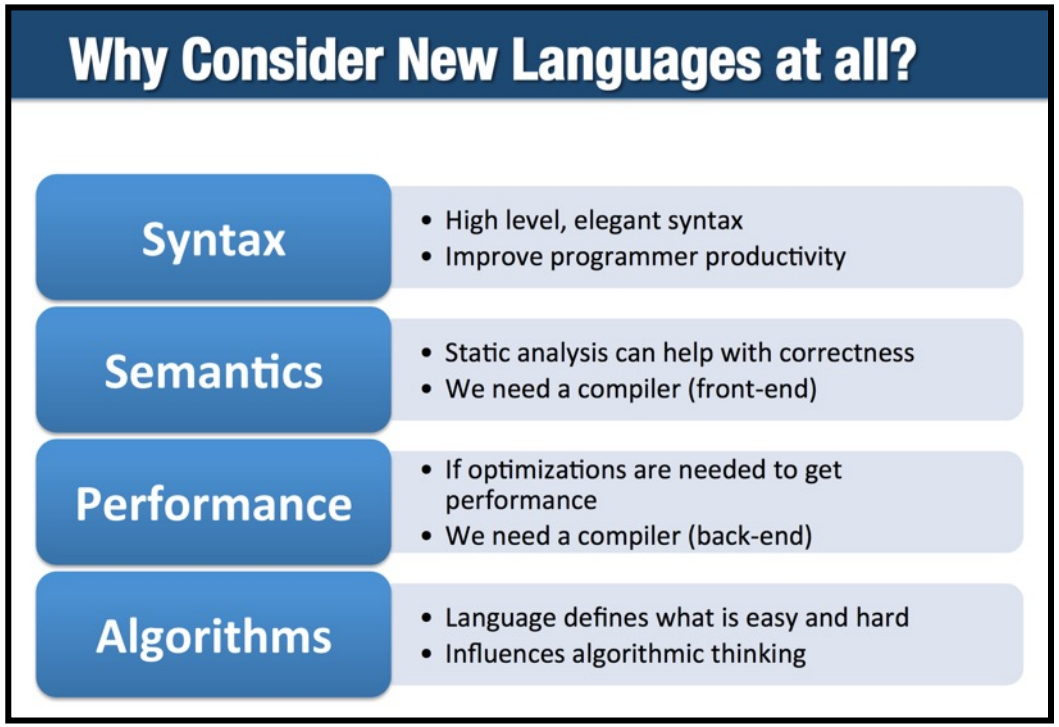
IV. Chapel Aggregators

V. Arkouda and Aggregation

VI. Wrap-up

WHY CREATE A NEW LANGUAGE?

- **Because parallel programmers deserve better**
  - the state of the art for HPC is a mish-mash of libraries, pragmas, and extensions
  - parallelism and locality are concerns that deserve first-class language features



[Image Source:
Kathy Yelick's (UC Berkeley, LBNL)
CHIUW 2018 keynote:
Why Languages Matter More Than Ever,
used with permission]

- **And because existing languages don't fit our desires…**

CHAPEL, RELATIVE TO OTHER LANGUAGES

Chapel strives to be as…

…**programmable** as Python

…**fast** as Fortran

…**scalable** as MPI, SHMEM, or UPC

…**portable** as C

…**flexible** as C++

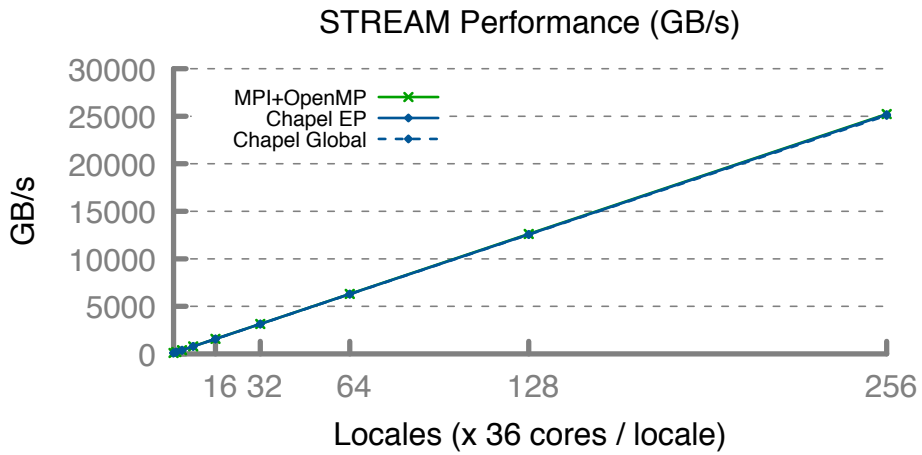
…**fun** as [your favorite programming language]

CHAPEL BENCHMARKS TEND TO BE CONCISE, CLEAR, AND COMPETITIVE

STREAM TRIAD: C + MPI + OPENMP

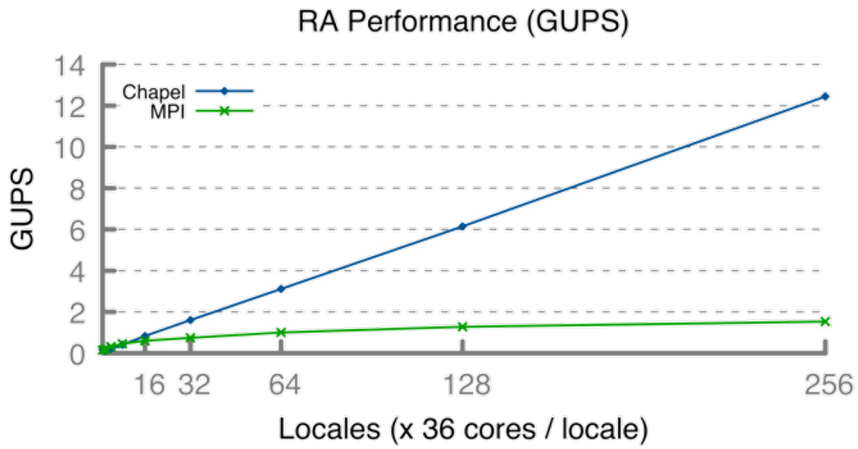
```
#include <hpcc.h>
#ifdef _OPENMP
#include <omp.h>
#endif

static int VectorSize;
static double *a, *b, *c;

int HPCC_StarStream(HPCC_Params *params) {
  int myRank, commSize;
  int rv, errCount;
  MPI_Comm comm = MPI_COMM_WORLD;

  MPI_Comm_size( comm, &commSize );
  MPI_Comm_rank( comm, &myRank );

  rv = HPCC_Stream( params, 0 == myRank);
  MPI_Reduce( &rv, &errCount, 1, MPI_INT, MPI_SUM, 0, comm );

  return errCount;
}

int HPCC_Stream(HPCC_Params *params, int doIO) {
  register int j;
  double  scalar;

  VectorSize = HPCC_LocalVectorSize( params, 3, sizeof(double), 0 );

  a = HPCC_XMALLOC( double, VectorSize );
  b = HPCC_XMALLOC( double, VectorSize );
  c = HPCC_XMALLOC( double, VectorSize );

  if (!a || !b || !c) {
    if (c) HPCC_free(c);
    if (b) HPCC_free(b);
    if (a) HPCC_free(a);
    if (doIO) {
      fprintf( outFile, "Failed to allocate memory
      fclose( outFile );
    }
    return 1;
  }

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++) {
    b[j] = 2.0;
    c[j] = 1.0;
  }
  scalar = 3.0;

#ifdef _OPENMP
#pragma omp parallel for
#endif
  for (j=0; j<VectorSize; j++)
    a[j] = b[j]+scalar*c[j];

  HPCC_free(c);
  HPCC_free(b);
  HPCC_free(a);

  return 0;
}
```

```
use BlockDist;

config const m = 1000,
             alpha = 3.0;
const Dom = {1..m} dmapped …;
var A, B, C: [Dom] real;

B = 2.0;
C = 1.0;

A = B + alpha * C;
```

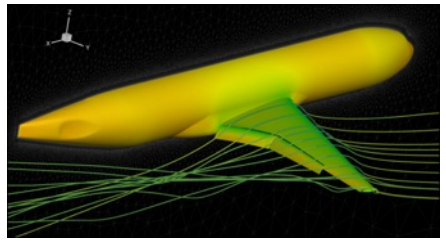


HPCC RA: MPI KERNEL

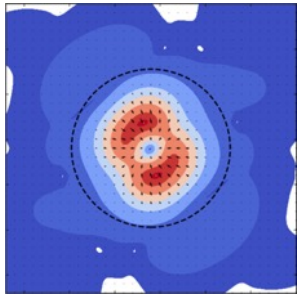
```
…
forall (_, r) in zip(Updates, RAStream()) do
  T[r & indexMask].xor(r);
…
```



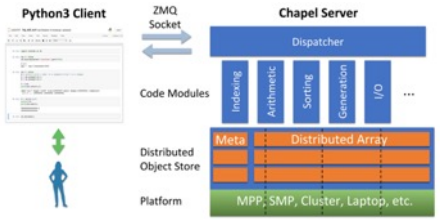
NOTABLE CURRENT APPLICATIONS OF CHAPEL



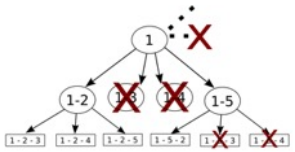
CHAMPS: 3D Unstructured CFD
Éric Laurendeau, Simon Bourgault-Côté, Matthieu Parenteau, et al.
École Polytechnique Montréal
~48k lines of Chapel



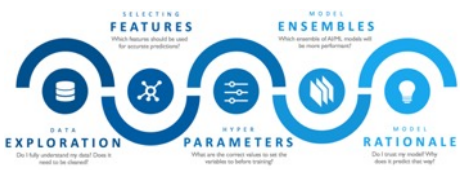
ChplUltra: Simulating Ultralight Dark Matter
Nikhil Padmanabhan, J. Luna Zagorac, Richard Easther, *et al.*
Yale University / University of Auckland



Arkouda: NumPy at Massive Scale
Mike Merrill, Bill Reus, et al.
US DOD
~16k lines of Chapel



ChOp: Chapel-based Optimization
Tiago Carneiro, Nouredine Melab, *et al.*
INRIA Lille, France



CrayAI: Distributed Machine Learning
Hewlett Packard Enterprise

?

Your Project Here?

CHAPEL'S MULTIRESOLUTION PHILOSOPHY

1. Users should be able to program at high levels of abstraction and get good performance

```
Dst = Src[Inds];     // whole-array index gather
```

2. Yet, when more control / better performance is needed, they can drop to lower levels…

```
forall (d, i) in zip(Dst, Inds) do    // parallel loop-based index gather
  d = Src[i];
```

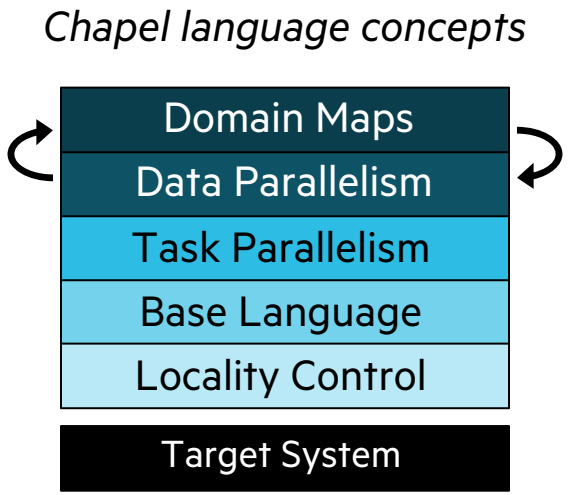
…and even lower levels, as necessary…

```
coforall loc in Dst.targetLocales do    // explicit SPMD-style index gather
  on loc do
    forall i in Dst.localSubdomain do
      Dst.localAccess[i] = Src[Inds.localAccess[i]];
```

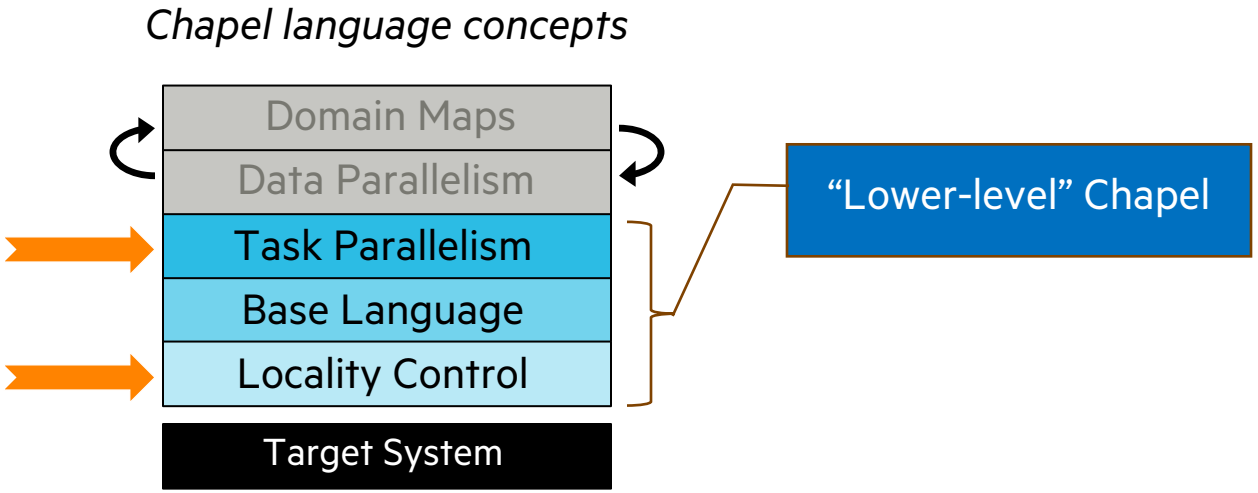
…where "calling out to C / CUDA / MPI / etc." is effectively the lowest level

3. Chapel builds its higher-level abstractions in terms of the lower-level ones to guarantee compatibility

CHAPEL'S MULTIRESOLUTION FEATURE STACK



CHAPEL'S "LOWER-LEVEL" FEATURES



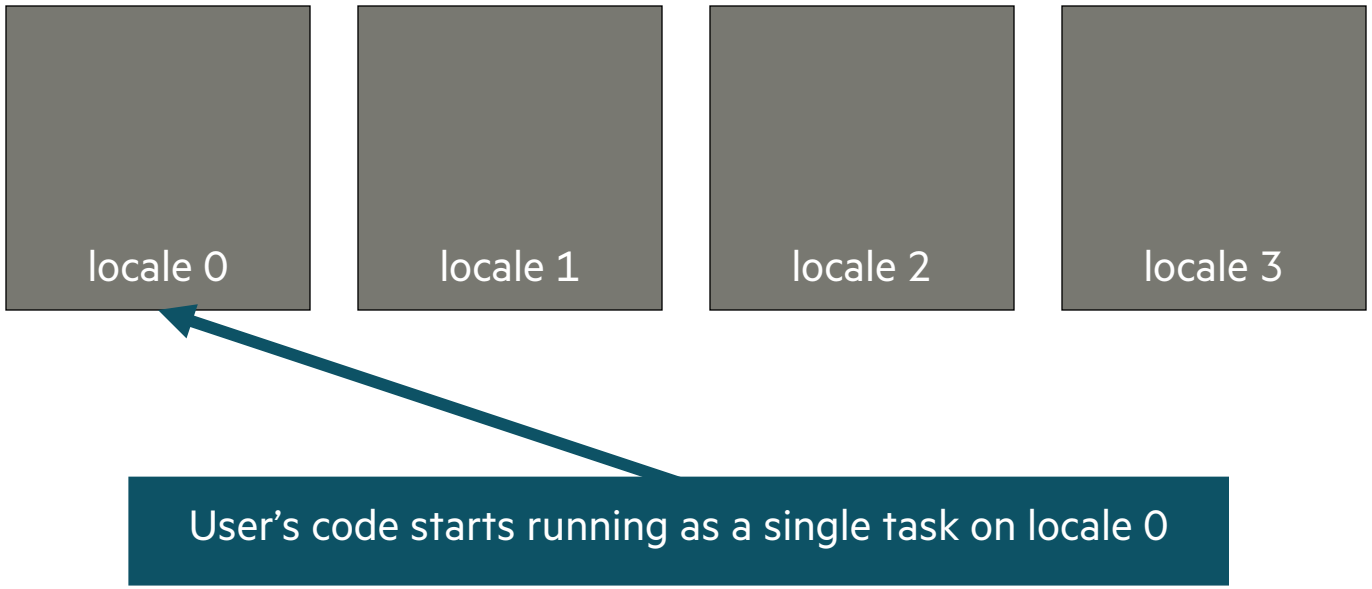

“LOW-LEVEL”
CHAPEL FEATURES

CHAPEL TERMINOLOGY: LOCALES

- Locales can run tasks and store variables
  - Think “compute node” on a parallel system
  - User specifies number of locales on executable’s command-line

```
prompt> ./myChapelProgram --numLocales=4    # or ‘-nl 4’
```

`Locales` array:



TASK-PARALLEL “HELLO WORLD”

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

TASK-PARALLEL "HELLO WORLD"

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

'here' refers to the locale on which we're currently running

how many processing units (think "cores") does my locale have?

what's my locale's name?

TASK-PARALLEL “HELLO WORLD”

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

a 'coforall' loop executes each iteration as an independent task

```
prompt> chpl helloTaskPar.chpl
prompt> ./helloTaskPar
Hello from task 1 of 4 on n1032
Hello from task 4 of 4 on n1032
Hello from task 3 of 4 on n1032
Hello from task 2 of 4 on n1032
```

TASK-PARALLEL “HELLO WORLD”

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

```
prompt> chpl helloTaskPar.chpl
prompt> ./helloTaskPar
Hello from task 1 of 4 on n1032
Hello from task 4 of 4 on n1032
Hello from task 3 of 4 on n1032
Hello from task 2 of 4 on n1032
```

So far, this is a shared-memory program

Nothing refers to remote locales, explicitly or implicitly

TASK-PARALLEL “HELLO WORLD”

helloTaskPar.chpl

```
const numTasks = here.numPUs();
coforall tid in 1..numTasks do
  writef("Hello from task %n of %n on %s\n",
         tid, numTasks, here.name);
```

TASK-PARALLEL "HELLO WORLD" (DISTRIBUTED VERSION)

helloTaskPar.chpl

```
coforall loc in Locales {
  on loc {
    const numTasks = here.numPUs();
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n on %s\n",
             tid, numTasks, here.name);
  }
}
```

TASK-PARALLEL "HELLO WORLD" (DISTRIBUTED VERSION)

helloTaskPar.chpl

```
coforall loc in Locales {
  on loc {
    const numTasks = here.numPUs();
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n on %s\n",
             tid, numTasks, here.name);
  }
}
```

create a task per locale on which the program is running

have each task run 'on' its locale

then print a message per core, as before

```
prompt> chpl helloTaskPar.chpl
prompt> ./helloTaskPar -numLocales=4
Hello from task 1 of 4 on n1032
Hello from task 4 of 4 on n1032
Hello from task 1 of 4 on n1034
Hello from task 2 of 4 on n1032
Hello from task 1 of 4 on n1033
Hello from task 3 of 4 on n1034
Hello from task 1 of 4 on n1035
…
```

DIFFERENCES BETWEEN CHAPEL AND TRADITIONAL PGAS / SHMEM

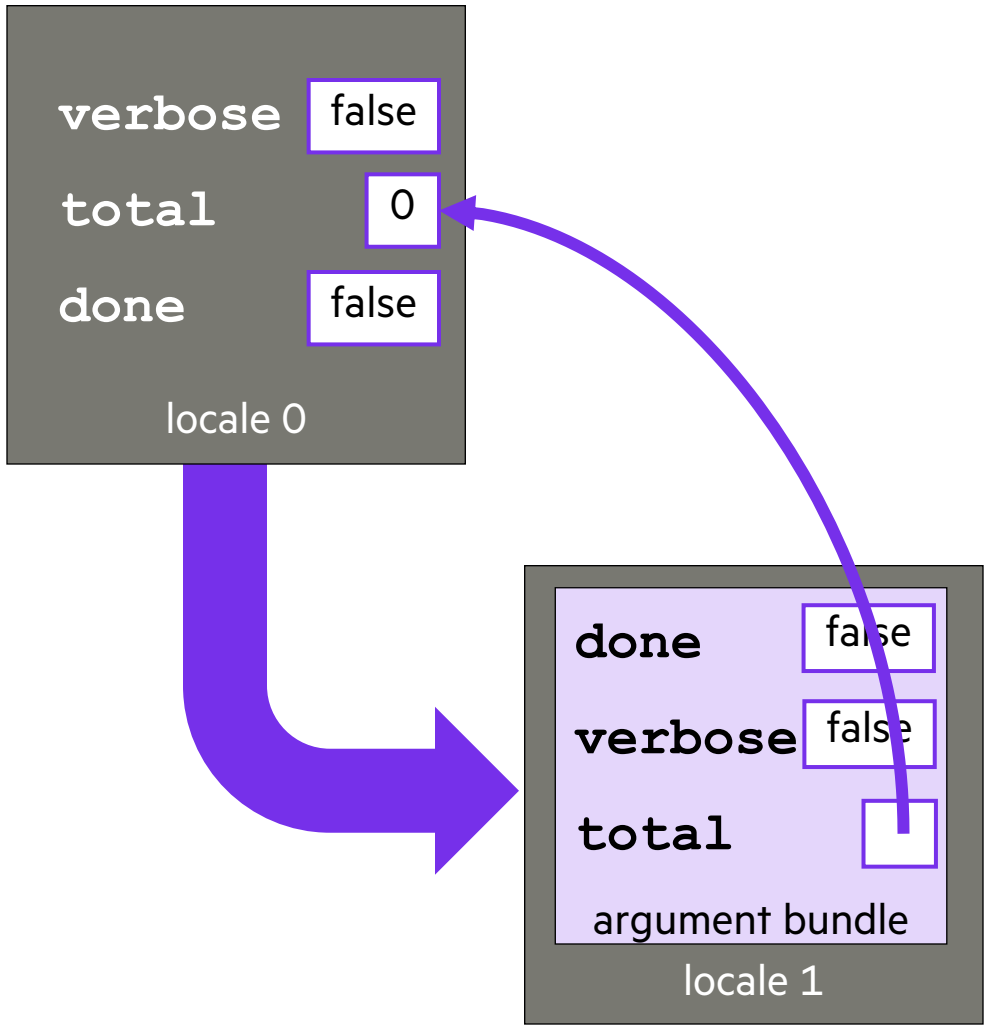
1. Chapel supports a post-SPMD execution model
   - **traditional PGAS:** all PEs/ranks/threads start by executing 'main'
   - **Chapel:** a single task executes 'main' on locale 0 and additional parallelism* is introduced from there

(* = local or distributed)

CHAPEL'S PARTITIONED GLOBAL NAMESPACE

onClause.chpl

```
const verbose = false;
var total = 0,
    done = false;

…

on Locales[1] {
  if !done {
    if verbose then
      writef("Adding locale 1's contribution");
    total += computeMyContribution();
  }
}
```



DIFFERENCES BETWEEN CHAPEL AND TRADITIONAL PGAS / SHMEM

1. Chapel supports a post-SPMD execution model
   - **traditional PGAS:** all ranks/threads/PEs start by executing 'main'
   - **Chapel:** a single task executes 'main' on locale 0 and additional parallelism* is introduced from there

   (* = local or distributed)

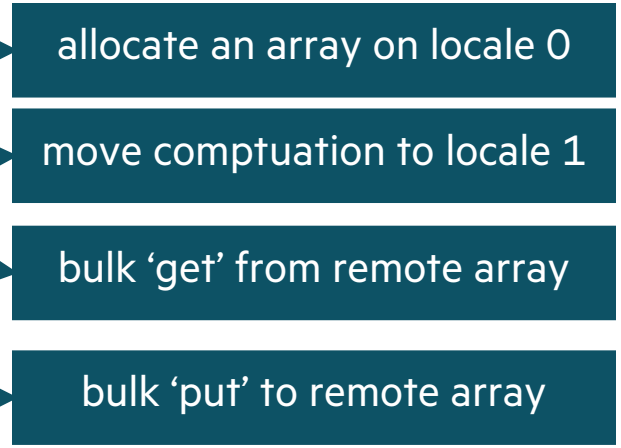
2. Chapel's partitioned global address space is also post-SPMD
   - **traditional PGAS:** "I have a variable named 'x', so you must too, and therefore I can refer to yours"
   - **Chapel:** "I see variable 'x' in my lexical scope, so I can refer to it, whether it's local or remote"

One outcome of these differences is that Chapel feels much more like traditional programming
Another is that Chapel has no real need for a symmetric heap

BULK COMMUNICATION IN CHAPEL: A TOOL FOR MANUAL AGGREGATION

bulkComm.chpl

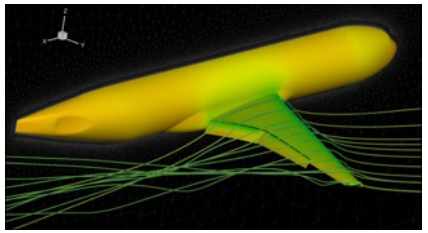
```
var Buff: [0..<buffSize] real;

on Locales[1] {
  var LocBuff = Buff;

  processData(LocBuff);
  Buff = LocBuff;
}
```

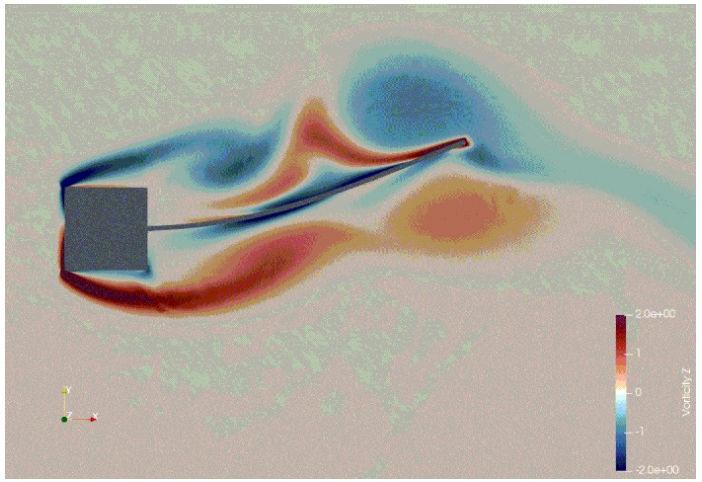


CHAMPS SUMMARY

What is it?

- 3D unstructured CFD framework for airplane simulation
- ~48k lines of Chapel written from scratch in ~2 years



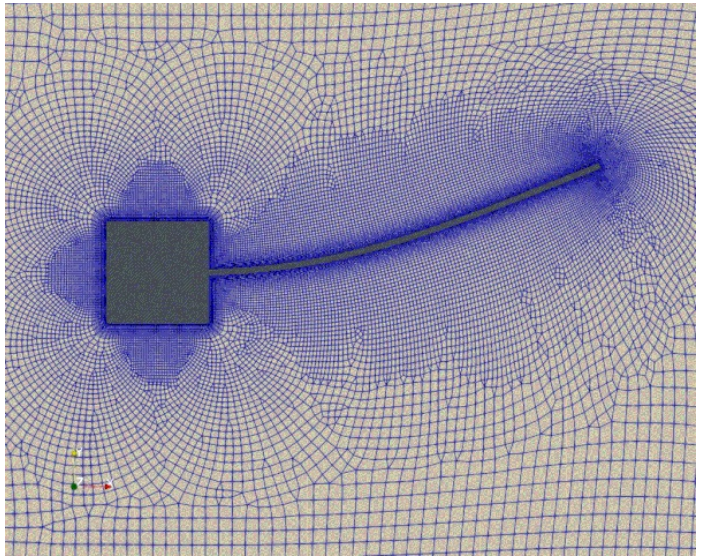


Who wrote it?

- Professor Eric Laurendeau's team at Polytechnique Montreal

Why Chapel?

- performance and scalability competitive with MPI + C++
- students found it more productive to use
  - senior students have reduced time-to-science
  - junior students can now accomplish in 3 months what had taken ~2 years
- achieving competitive results w.r.t. established, world-class frameworks from Stanford, MIT, etc.



MANUALLY AGGREGATED BULK COMMUNICATION IN CHAMPS

```
override proc exchange(zone, bZone) {
  recvBuffer_ = bZone.remoteIcGlobalIndex_.donorBuffer_;

  const haloSubDomain = bZone.haloSubDomain_;

  ref facetsCon = zone.facetsConnectivity_,
      elemCon = zone.elementsConnectivity_;

  for (haloIndex, iFacetTimesStride) in zip(haloSubDomain, 0.. by stride_) {
    elemCon.elementsGlobalIndex_[haloIndex] = recvBuffer_[iFacetTimesStride];
  }
}
```

copy remote donor buffer to current locale

copy from buffer to local physics data structures


CHAPEL AGGREGATORS

BALE INDEX GATHER IN CHAPEL

```
use BlockDist, Random, CopyAggregation;

const numTasks = numLocales * here.maxTaskPar;
config const N = 1000000,   // number of updates per task
             M = 10000;     // number of entries in the table per task

const D = newBlockDom(0..<M*numTasks);
var Src: [D] int = D;
const UpdatesDom = newBlockDom(0..<N*numTasks);
var Dst, Rindex: [UpdatesDom] int;

fillRandom(Rindex, 208);
Rindex = mod(Rindex, M*numTasks);
```

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

BALE INDEX GATHER KERNEL IN CHAPEL: NAÏVE VERSION

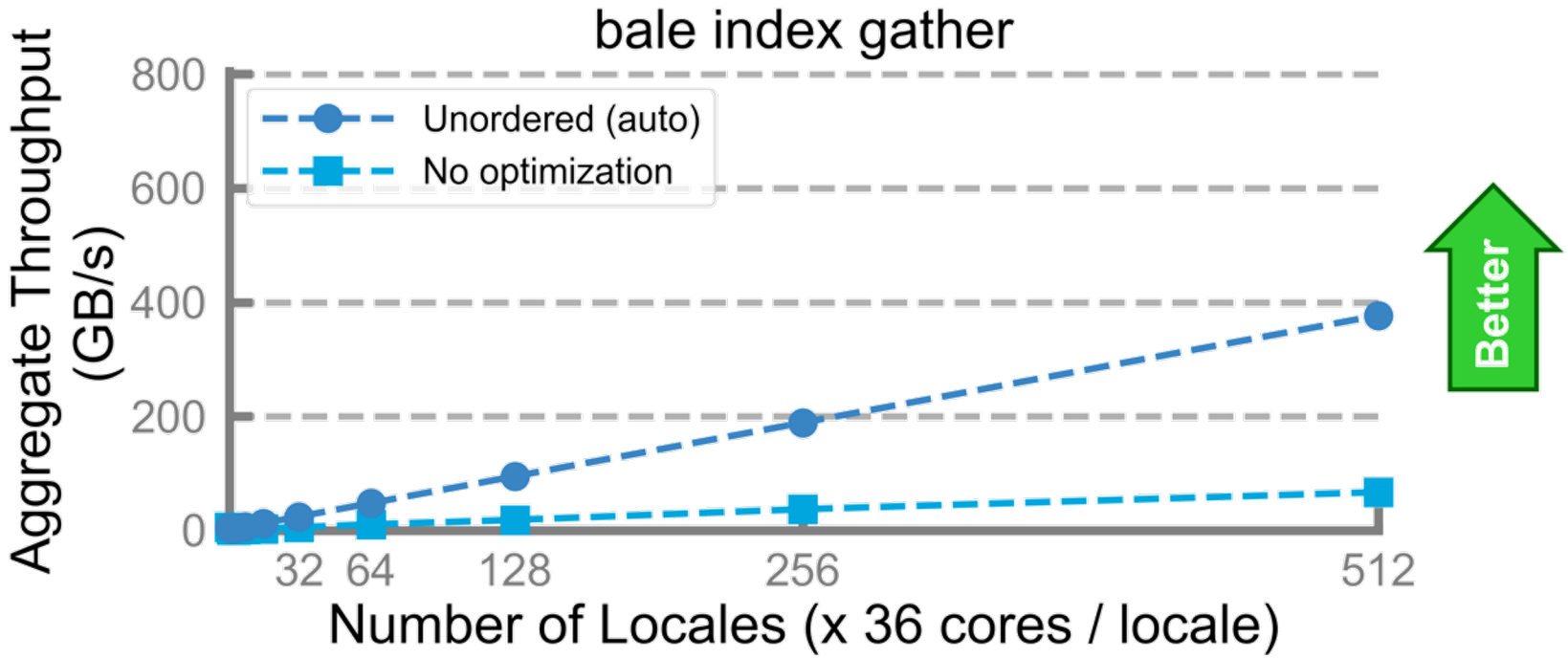
```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

'*Dst*' and '*Inds*' are distributed arrays with *numUpdates* elements

'*Src*' is a distributed array with *numEntries* elements

BALE INDEX GATHER KERNEL IN CHAPEL: NAÏVE VERSION

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```



BALE INDEX GATHER KERNEL IN CHAPEL: AGGREGATOR VERSION

```
use CopyAggregation;

// Aggregated index gather
forall (d, i) in zip(Dst, Inds) with (var agg = new SrcAggregator(int)) do
  agg.copy(d, Src[i]);
```

'use' the module providing the aggregators

'with (var ...)' creates a variable per task that's executing the 'forall' loop

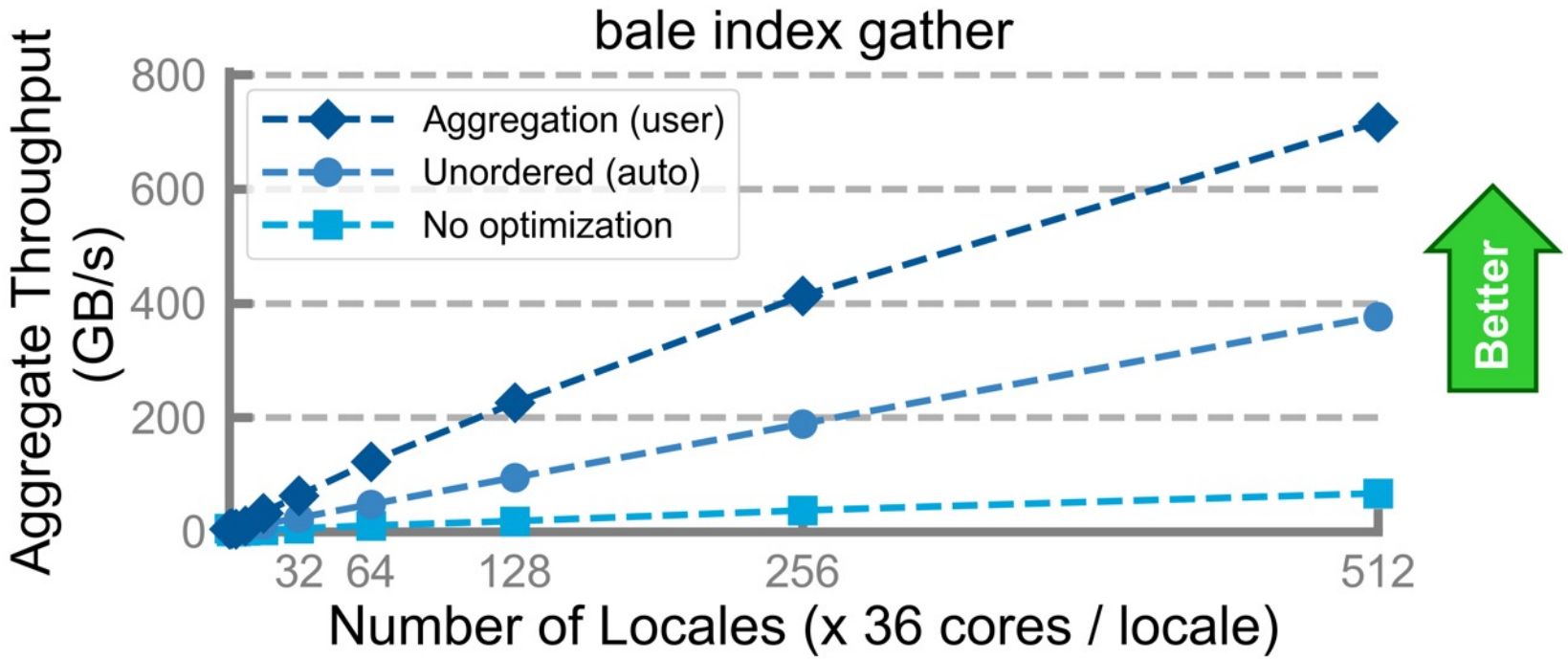
Here, we're giving each task a "source aggregator", *agg*, which aggregates remote 'gets' locally, then performs them

To use it, we simply replace the assignment with 'agg.copy'

As the aggregator's buffers fill up, it automatically performs the communications with the remote locale

BALE INDEX GATHER KERNEL IN CHAPEL: AGGREGATOR VERSION

```
use CopyAggregation;

// Aggregated index gather
forall (d, i) in zip(Dst, Inds) with (var agg = new SrcAggregator(int)) do
  agg.copy(d, Src[i]);
```



IMPLEMENTING CHAPEL'S AGGREGATORS

- Chapel's aggregators are implemented as Chapel source code
  - no language or compiler changes were required
  - initial implementation only relied on user-facing features
    - current optimized version calls into put/get routines from Chapel runtime
  - Relies upon:
    - standard language features:
      - OOP: records, initializers, de-initializers
      - arrays
      - access to C-level pointers and dereferences
    - Chapel features that you've seen:
      - global namespace
      - task-local variables
  - ~100 lines of reasonably straightforward code to implement SrcAggregator
    - (~420 lines for entire 'CopyAggregation' module)
- Developed by Elliot Ronaghan, 2020–present

INITIAL SRC AGGREGATOR IMPLEMENTATION: EXCERPTS

```
record SrcAggregator {
  type elemType;
  var dstAddrs, srcAddrs: [LocaleSpace] [0..<bufferSize] addr;
  var bufferIdxs: [LocaleSpace] int;
  …
  proc flushBuffer(loc: int, ref bufferIdx) {
    var srcVals: [0..<bufferIdx] elemType;

    on Locales[loc] {
      const locSrcAddrs = srcAddrs[loc][0..<bufferIdx];
      var locSrcVals: [0..<bufferIdx] elemType;
      …   // fill the locSrcVals array
      srcVals = locSrcVals;
    }
    …   // assign the srcVals to the dstAddrs
  }
}
```

Arrays for buffering per-locale src/dest addresses

time to flush a buffer?

allocate a landing spot for the remote src values

move to the remote node to buffer src vals and copy them back

Bulk array copy to 'get' the src addresses

Declare a buffer to store the local src vals and fill it

Bulk array copy to 'put' src values back to original locale

Store src vals to dest addresses

INITIAL SRC AGGREGATOR IMPLEMENTATION: BULK PUT/GET OPS

```
record SrcAggregator {
  type elemType;
  var dstAddrs, srcAddrs: [LocaleSpace] [0..<bufferSize] addr;
  var bufferIdxs: [LocaleSpace] int;
  …
  proc flushBuffer(loc: int, ref bufferIdx) {
    var srcVals: [0..<bufferIdx] elemType;

    on Locales[loc] {
      const locSrcAddrs = srcAddrs[loc][0..<bufferIdx];
      var locSrcVals: [0..<bufferIdx] elemType;
      …   // fill the locSrcVals array
      srcVals = locSrcVals;
    }
    …   // assign the srcVals to the dstAddrs
  }
}
```

Bulk array copy to ‘get’ the src addresses

Bulk array copy to ‘put’ src values back to original locale

CHAPEL AGGREGATORS: ATTRACTIVE PROPERTIES

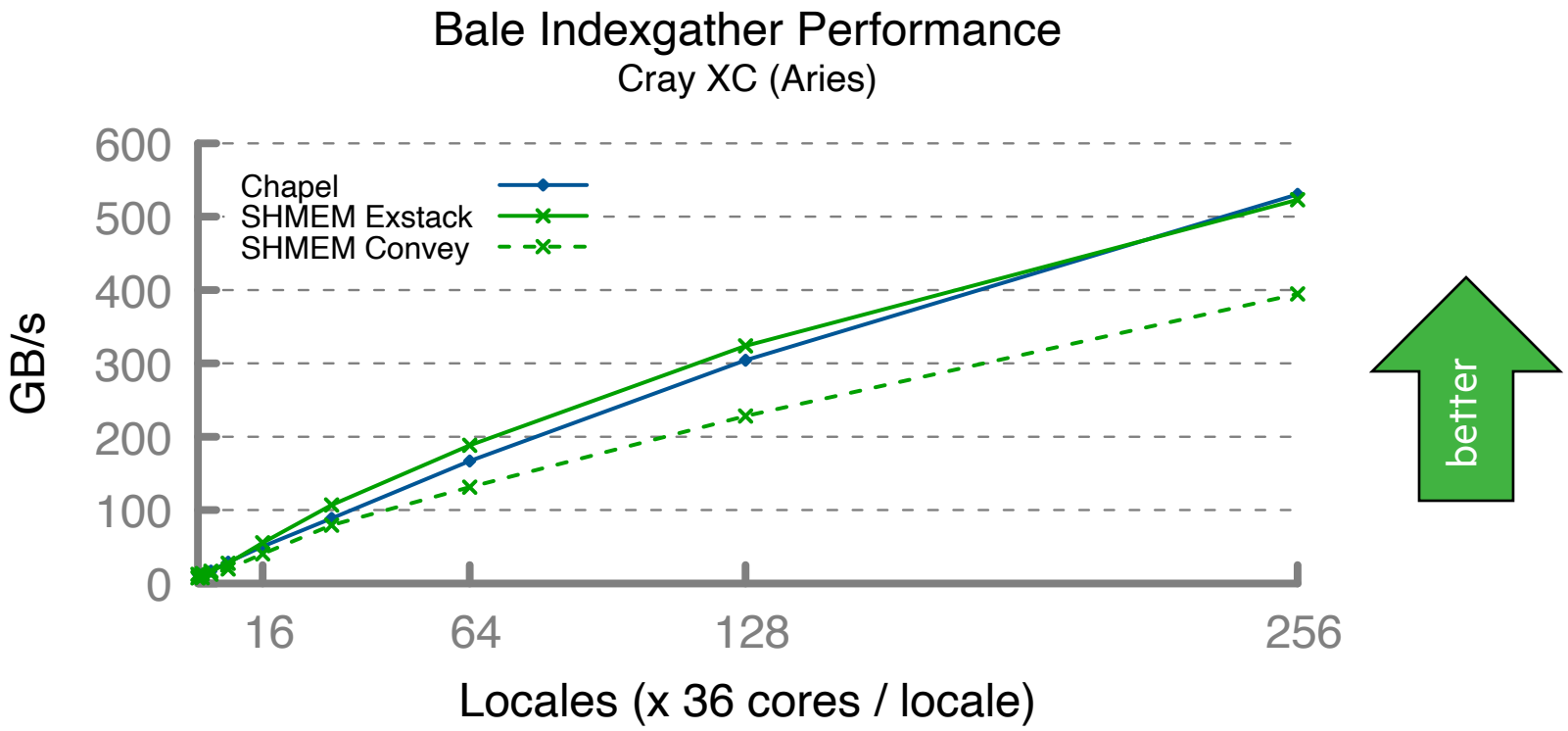
- More flexible than traditional aggregators:
  - **traditional aggregators:** like barriers or collectives, tend to assume everyone is involved and quasi-lockstep
  - **Chapel aggregators:** Chapel's post-SPMD nature relaxes traditional BSP constraints
    - tasks communicate with remote locales asynchronously, once a given buffer fills up
    - any subset of tasks/locales can utilize aggregators that target any locales *without those locales being involved*

- User-level tasks make the implementation efficient
  - Chapel leverages Sandia's Qthreads

- Performance is competitive with conventional techniques

AGGREGATION PERFORMANCE: CHAPEL VS. EXSTACK VS. CONVEY

- For Bale index gather, Chapel competes with Exstack on up to 256 nodes / 9k cores of Cray XC
  - These results are from October 2020
  - We have since done ~600-node runs with similar results



CAN WE AUTOMATE AGGREGATION?

Q: Is there an opportunity for the compiler to introduce aggregators automatically?

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```

user writes straightforward code
compiler optimizes as:

```
use CopyAggregation;

// Aggregated index gather
forall (d, i) in zip(Dst, Inds) with (var agg = new SrcAggregator(int)) do
  agg.copy(d, Src[i]);
```

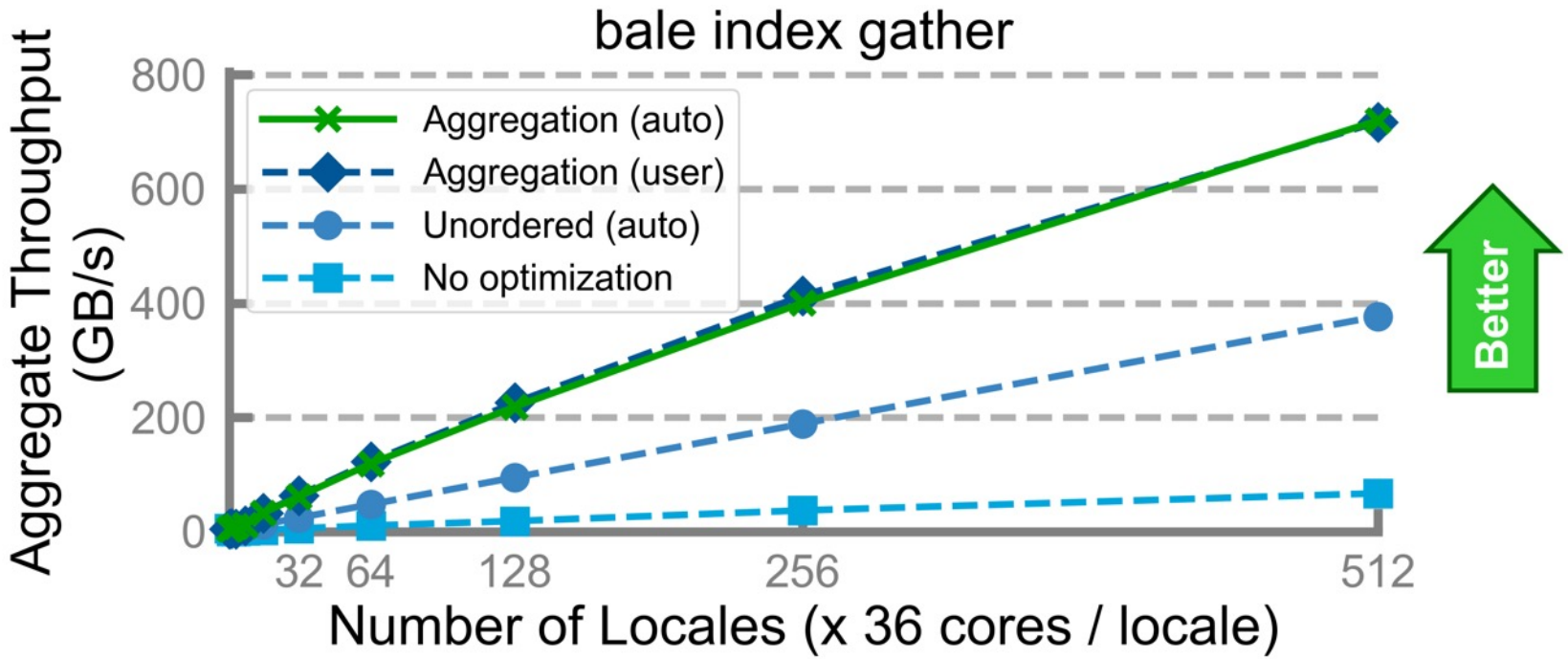
A: In many cases, yes

- developed by Engin Kayraklioglu, 2021
- combines previous 'unordered' analysis from HPCC RA with a new locality analysis of RHS/LHS expressions
- for details, see Engin's upcoming talk and paper at LCPC 2021, October 13–15: https://lcpc2021.github.io/

AUTO-AGGREGATION: IMPACT

- As a result, the naïve version can now compete with the user-written aggregators

```
// Naive index gather
forall (d, i) in zip(Dst, Inds) do
  d = Src[i];
```



SOUNDS GREAT, WHAT'S THE CATCH?

Q: Clean code, competitive performance and scalability, no modifications to the language or compiler…

…so, what's the catch?

A: Not a 'catch' per se, but currently, Chapel's aggregators only support copy-style operations

- Ultimately, want/need to support general operations ("user-defined aggregators")
  - In principle, not so different from the existing ones
  - **Limiting factor:** These would most naturally be expressed with first-class functions (FCFs)

    …but Chapel's support for FCFs is currently a bit weak

- That said, many interesting computations can be written with copy-style aggregation…

  …like Arkouda!


ARKOUDA AND AGGREGATION

MOTIVATION FOR ARKOUDA

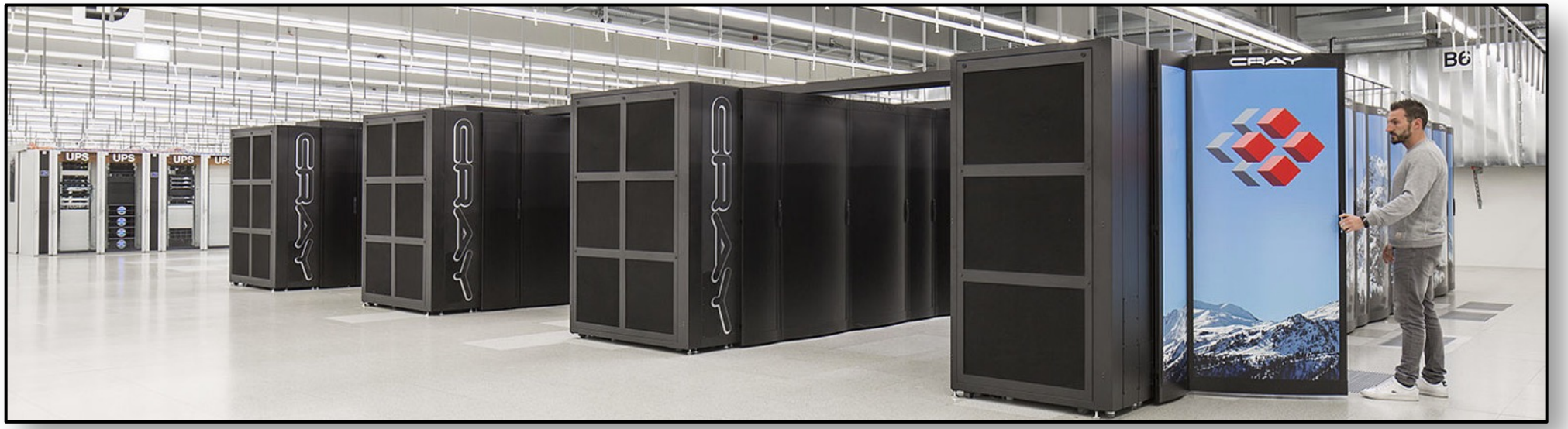
Motivation: Say you've got…

…a bunch of Python programmers

…HPC-scale data science problems to solve

…access to HPC systems

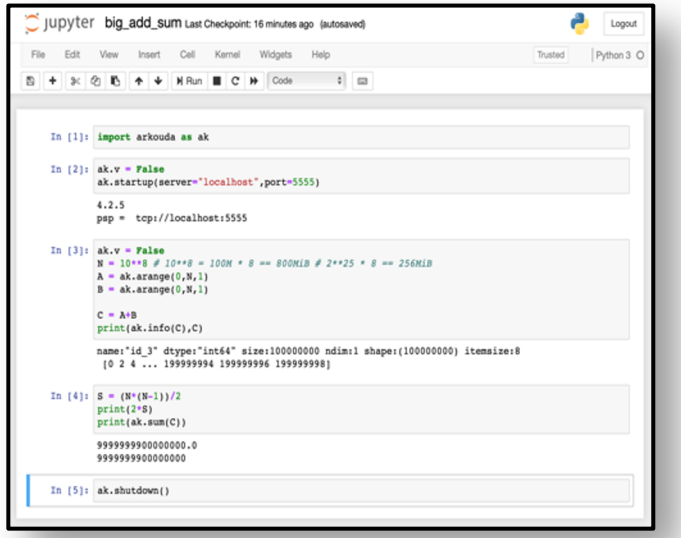
https://www.cscs.ch/computers/piz-daint/



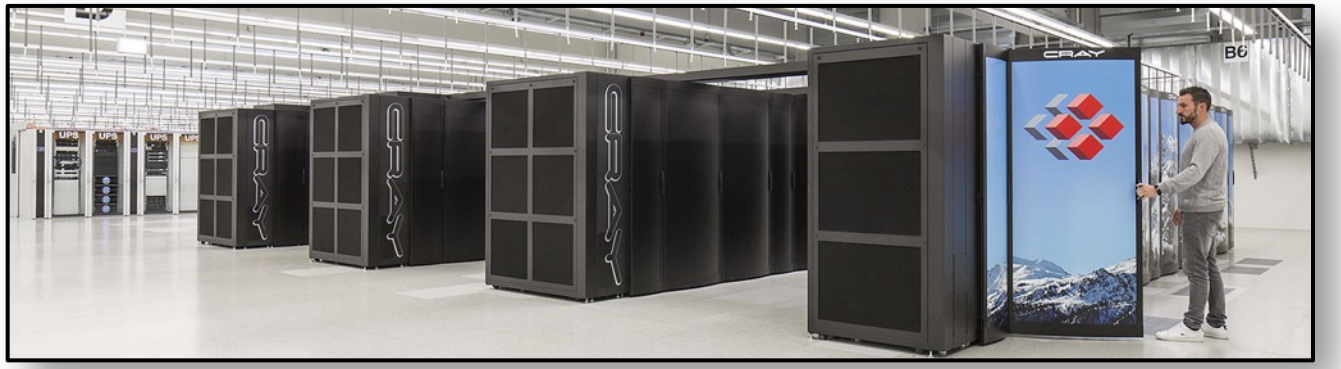
How will you leverage your Python programmers to get your work done?

ARKOUDA'S APPROACH

Arkouda Client
(written in Python)



Arkouda Server (written in Chapel)



Writes Python code in Jupyter
Invoking NumPy/Pandas ops

ARKOUDA SUMMARY

What is it?

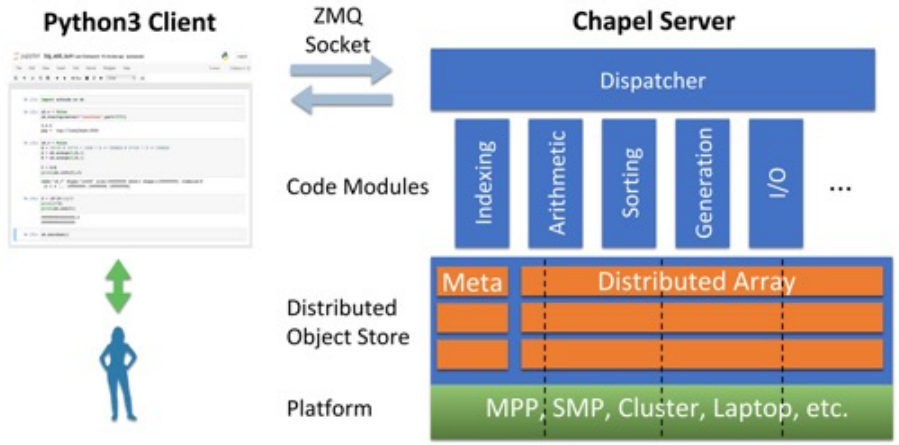
- "A workbench for data science at massive scales and interactive rates"
  - massive scales = multi-TB data sets
  - interactive rates = within the human thought loop (seconds to few minutes)
- ~16k lines of Chapel, largely written in 2019, continually improved since then

Who did it?

- Mike Merrill, Bill Reus, *et al.*, US DOD

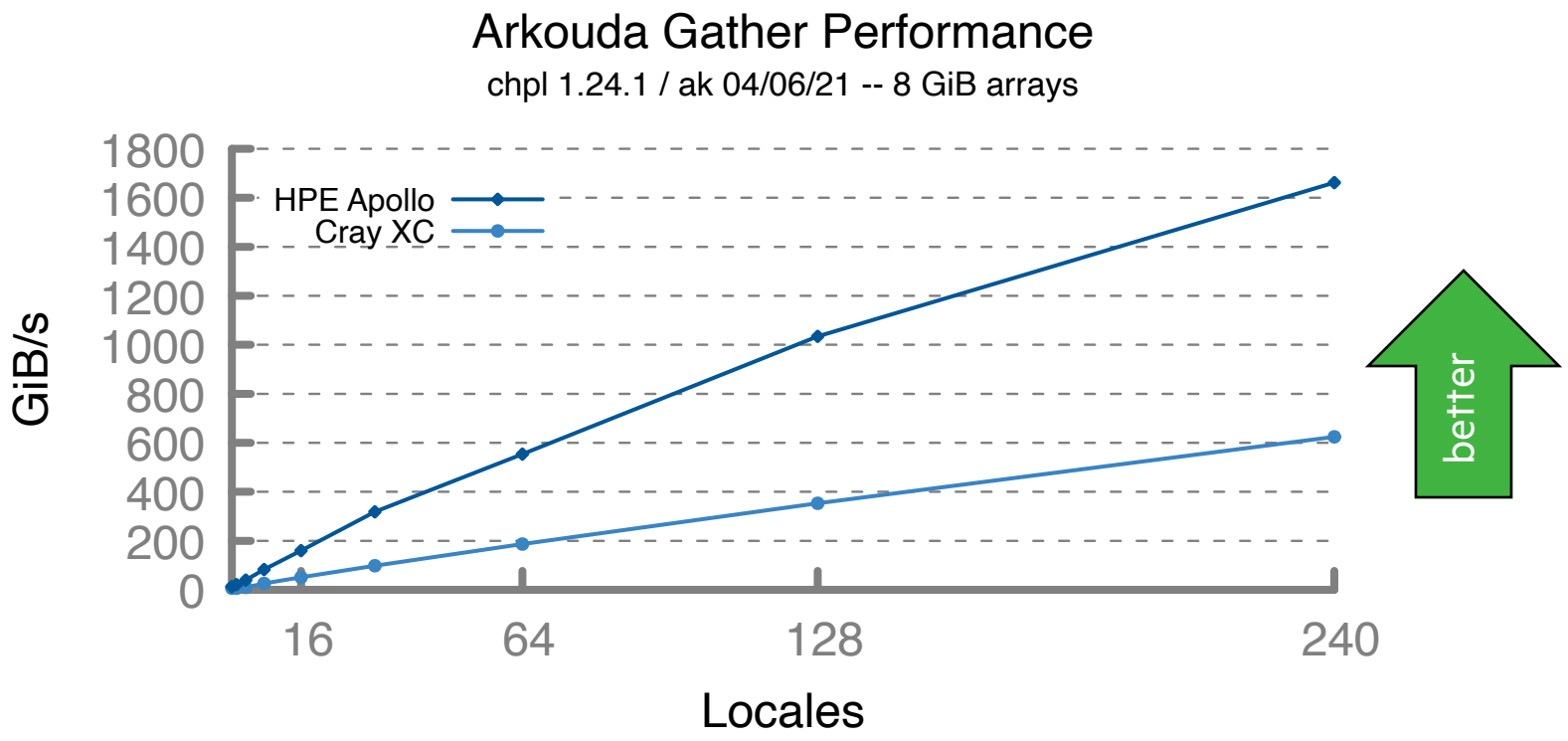
Why Chapel?

- great distributed array support
- ports from laptop to supercomputer
- high-level language with C-comparable performance
- close to Pythonic—doesn't repel Python users who look under the hood



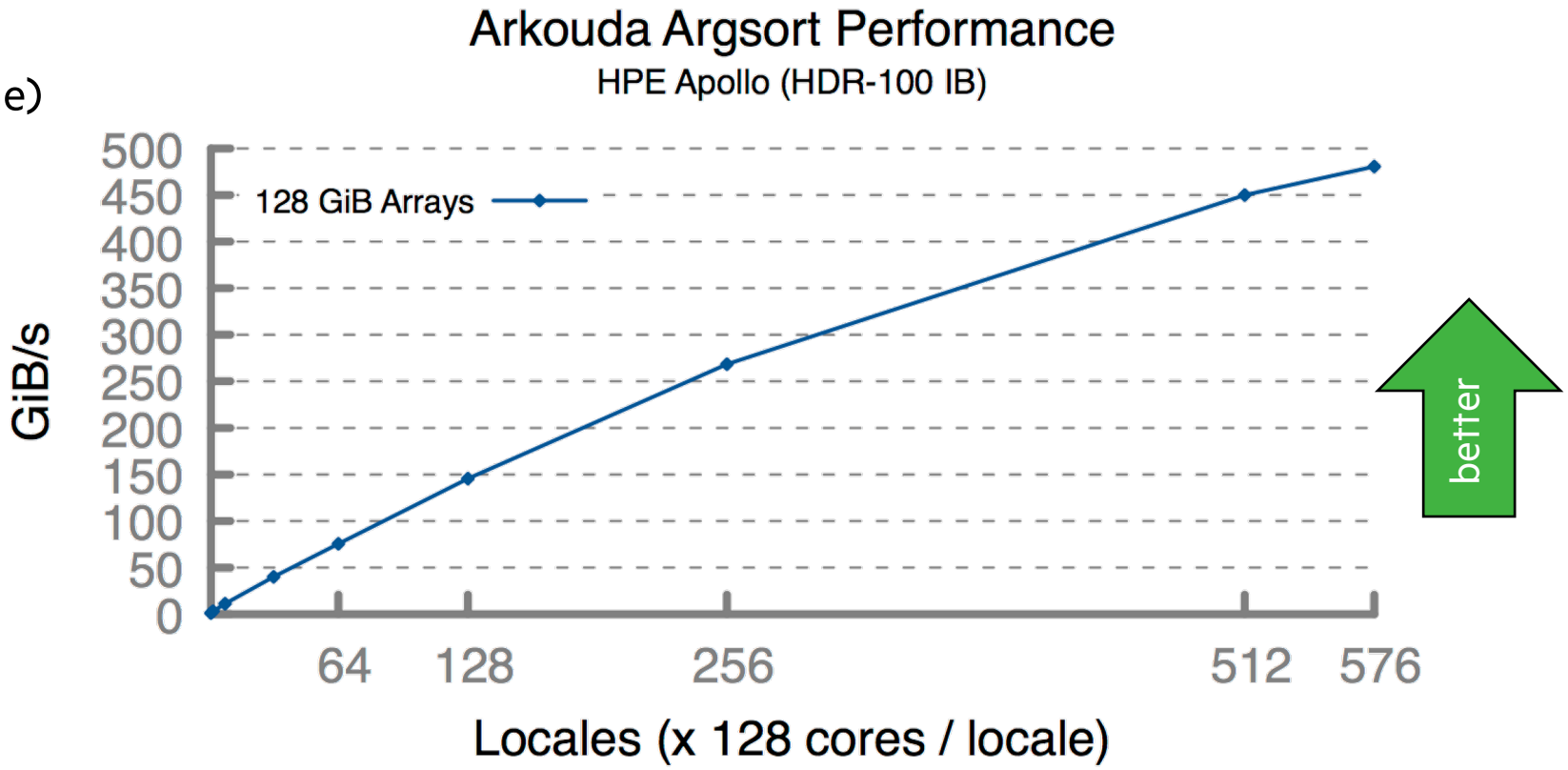
ARKOUDA GATHER

- For Arkouda's gather kernel, Chapel performance on a recent HPE Apollo system is well ahead of XC
  - These timings were taken in April 2021
  - System-level bugs hurt reference SHMEM performance, so no direct comparisons here



ARKOUDA ARGSORT: HERO RUN

- Recent hero run performed on a large Apollo system
  - 72 TiB of 8-byte values
  - 480 GiB/s (2.5 minutes elapsed time)
  - used 73,728 cores of AMD Rome
  - ~100 lines of Chapel code

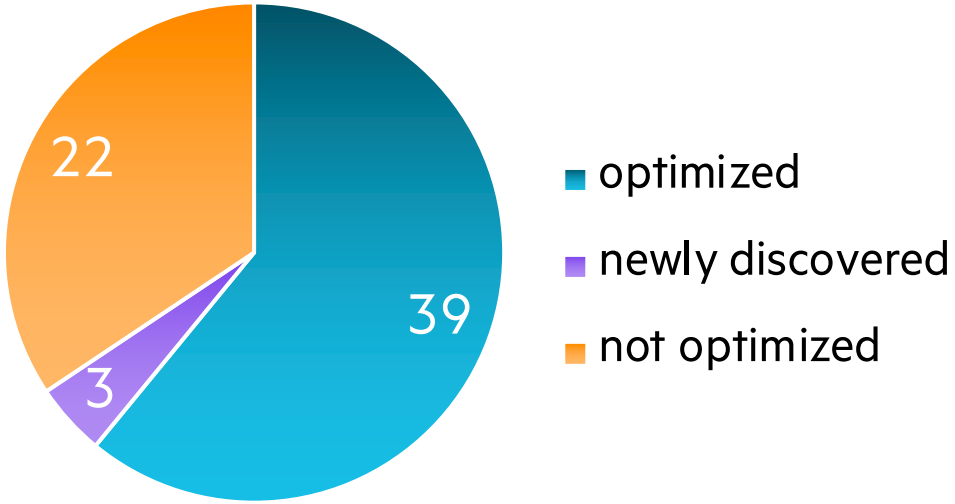


Aggregators have been key to getting results like these

ARKOUDA AND AUTO-AGGREGATION

- In Arkouda, we removed all manual aggregation from the source and applied auto-aggregation
  - 61 loops in total
    - 39 are optimized automatically
    - 22 are not
  - 3 cases that were not using aggregators were auto-optimized

  - The patterns where the aggregation does not fire:
    - 9: aggregation is not based on ‘forall’ loops
    - 6: compiler cannot prove that unordered operation is safe
    - 3: locality is hard to detect
    - 2: aggregated copy is not in the last statement of the body
    - 1: one side of the assignment is defined within the loop body
    - 1: needs further investigation




WRAP-UP

CHAPEL RESOURCES

Chapel homepage: https://chapel-lang.org

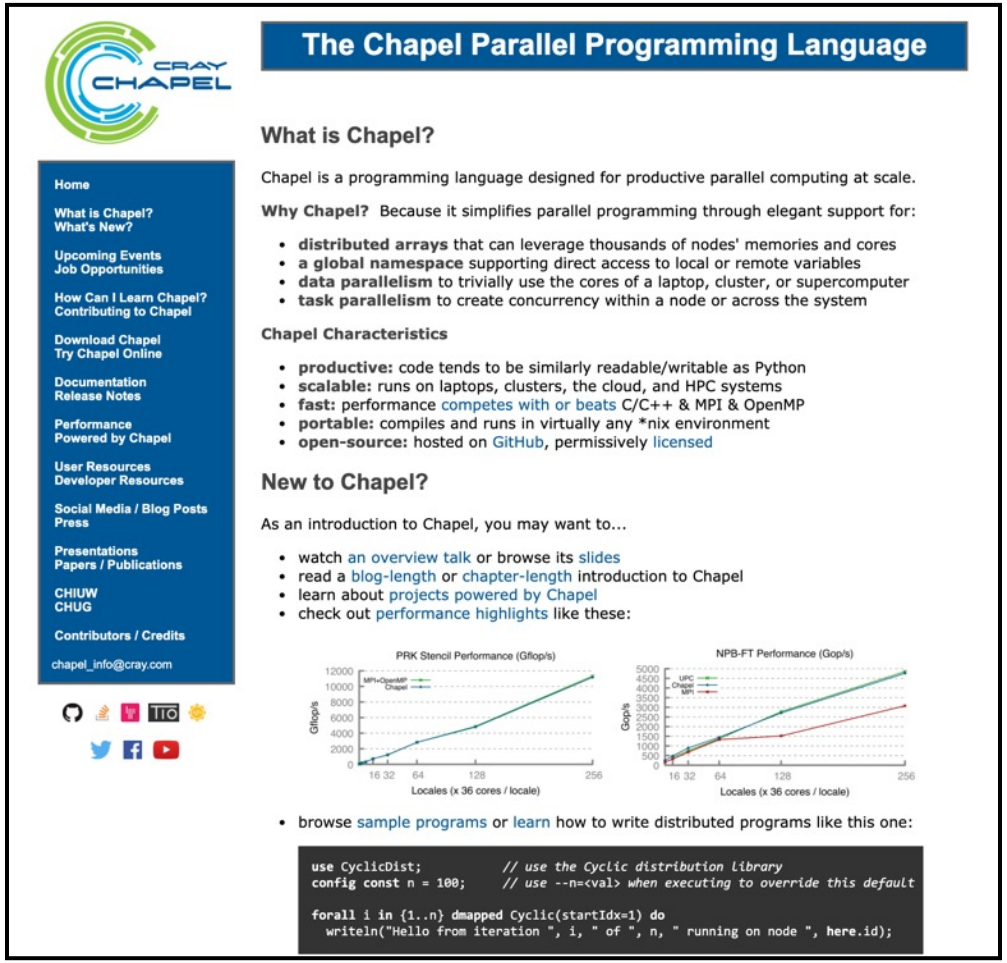
- (points to all other resources)

Social Media:

- Twitter: @ChapelLanguage
- Facebook: @ChapelLanguage
- YouTube: http://www.youtube.com/c/ChapelParallelProgrammingLanguage

Community Discussion / Support:

- Gitter: https://gitter.im/chapel-lang/chapel
- Discourse: https://chapel.discourse.group/
- Stack Overflow: https://stackoverflow.com/questions/tagged/chapel
- GitHub Issues: https://github.com/chapel-lang/chapel/issues



SUGGESTED READING / VIEWING

Chapel Overviews / History (in chronological order):

- *Chapel* chapter from *Programming Models for Parallel Computing*, MIT Press, edited by Pavan Balaji, November 2015
- *Chapel Comes of Age: Making Scalable Programming Productive*, Chamberlain et al., *CUG 2018*, May 2018
- Proceedings of the *8th Annual Chapel Implementers and Users Workshop* (CHIUW 2021), June 2021
- Chapel Release Notes — current version 1.24, April 2021

Arkouda:

- Bill Reus's CHIUW 2020 keynote talk: https://chapel-lang.org/CHIUW2020.html#keynote
- Arkouda GitHub repo and pointers to other resources: https://github.com/Bears-R-Us/arkouda

CHAMPS:

- Eric Laurendeau's CHIUW 2021 keynote talk: https://chapel-lang.org/CHIUW2021.html#keynote
  – two of his students also gave presentations at CHIUW 2021, also available from the URL above
- Another paper/presentation by his students at https://chapel-lang.org/papers.html (search "Laurendeau")

CHAPEL IS HIRING

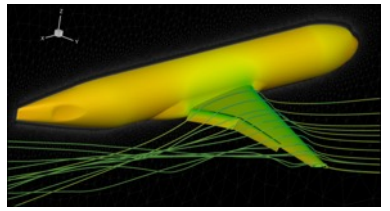
- Chapel team at HPE is currently 18.5 full-time employees
  - planning to add 1–2 more during 2021
  - see: chapel-lang.org/jobs.html

- During summers, we also host interns and mentor Google Summer of Code students

SUMMARY

Chapel is designed for productive parallel programming at scale

- recent users have reaped these benefits in 16k–48k-line applications



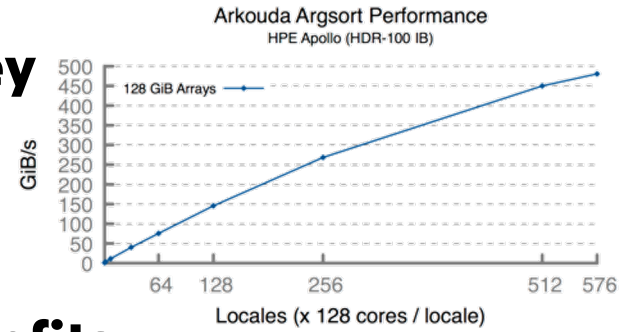
Though PGAS in nature, Chapel avoids SPMD / BSP assumptions

- parallelism is expressed in the source code starting from a single task
- lexical scoping simplifies PGAS-based communication
- the net result is a far more approachable distributed parallel language

```
coforall loc in Locales {
  on loc {
    const numTasks = here.numPUs();
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n on %s\n",
             tid, numTasks, here.name);
  }
}
```

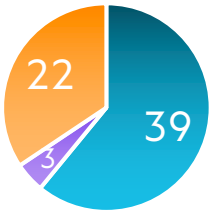
For gather/scatter/sort in Arkouda and Bale, copy aggregators are key

- Chapel's are implemented concisely and elegantly within the language
- performance rivals that of Exstack / Conveyors



Chapel's design and language-based nature provide optimization benefits

- e.g., automatic asynchronous operations (as in RA) and automatic aggregation (as in Arkouda / Bale)




THANK YOU
https://chapel-lang.org
@ChapelLanguage