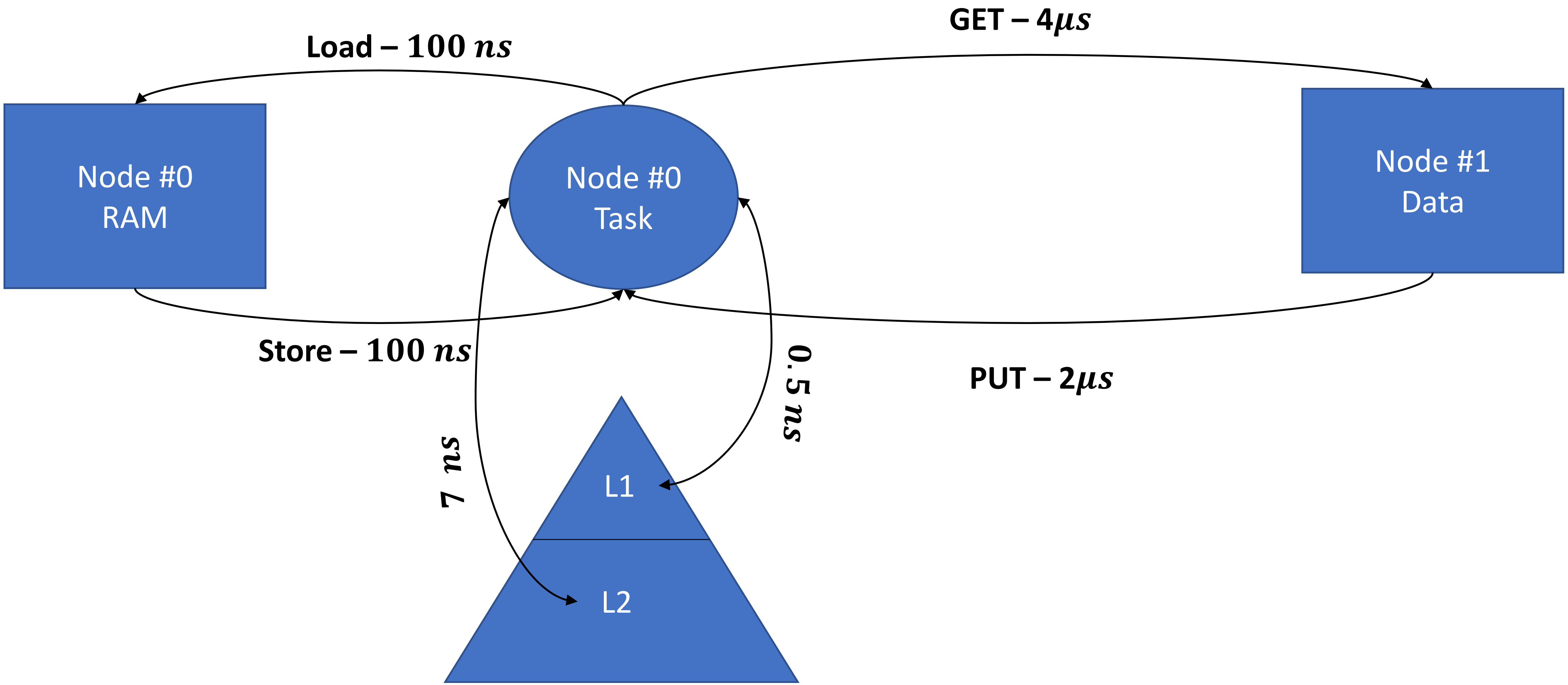
Chapel Aggregation Library (CAL)

By Louis Jenkins

The Problem

- Accessing remote data is slow
  - Multiple orders of magnitude slower to access than local memory



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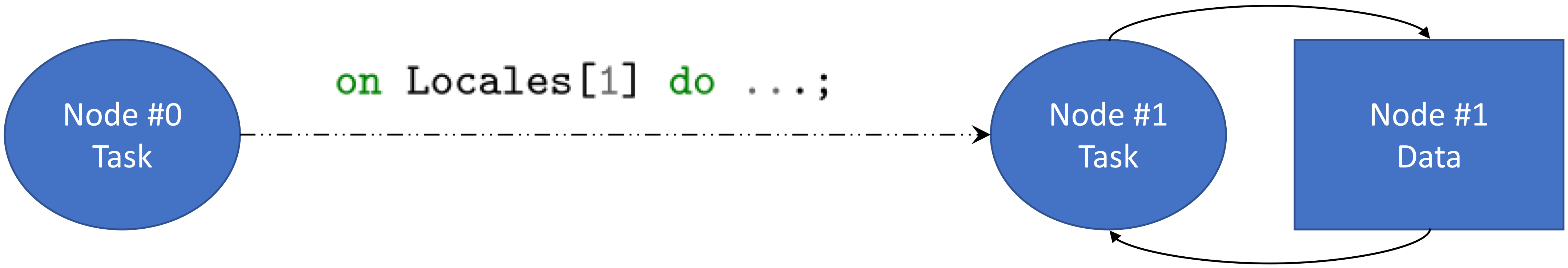
- “Moving the computation to the data” not always the best solution
  - Using an on statement requires migrating tasks to another locale



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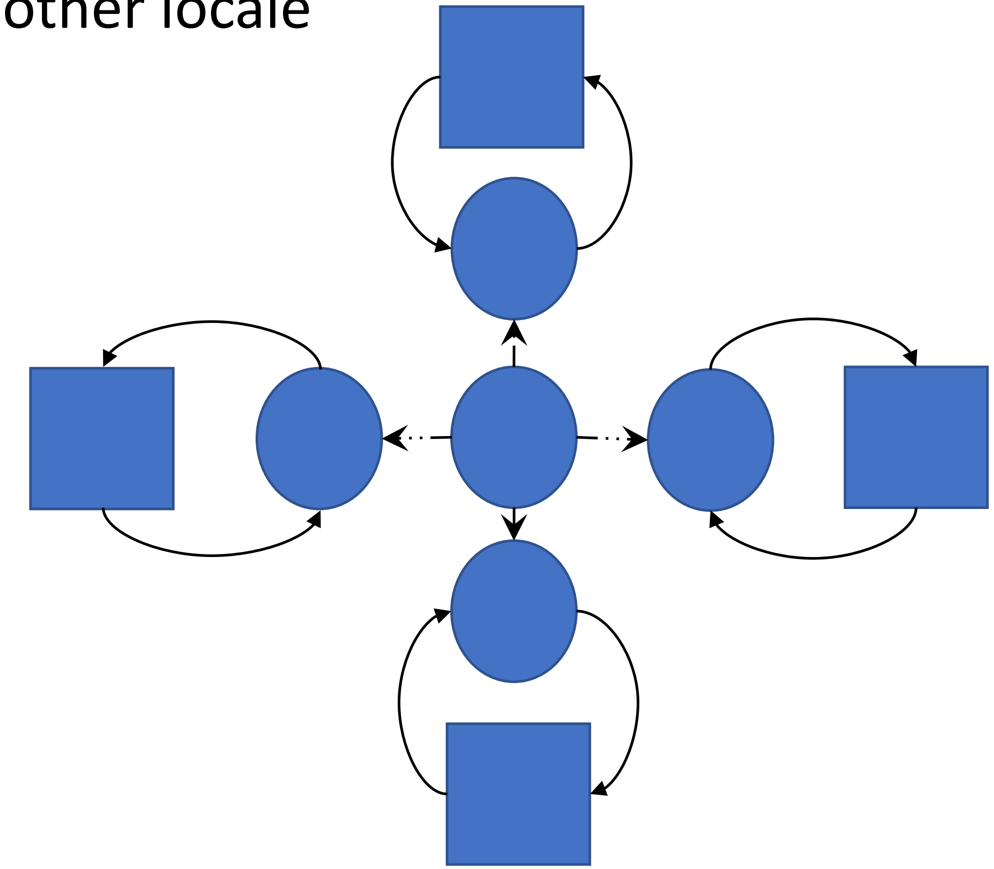

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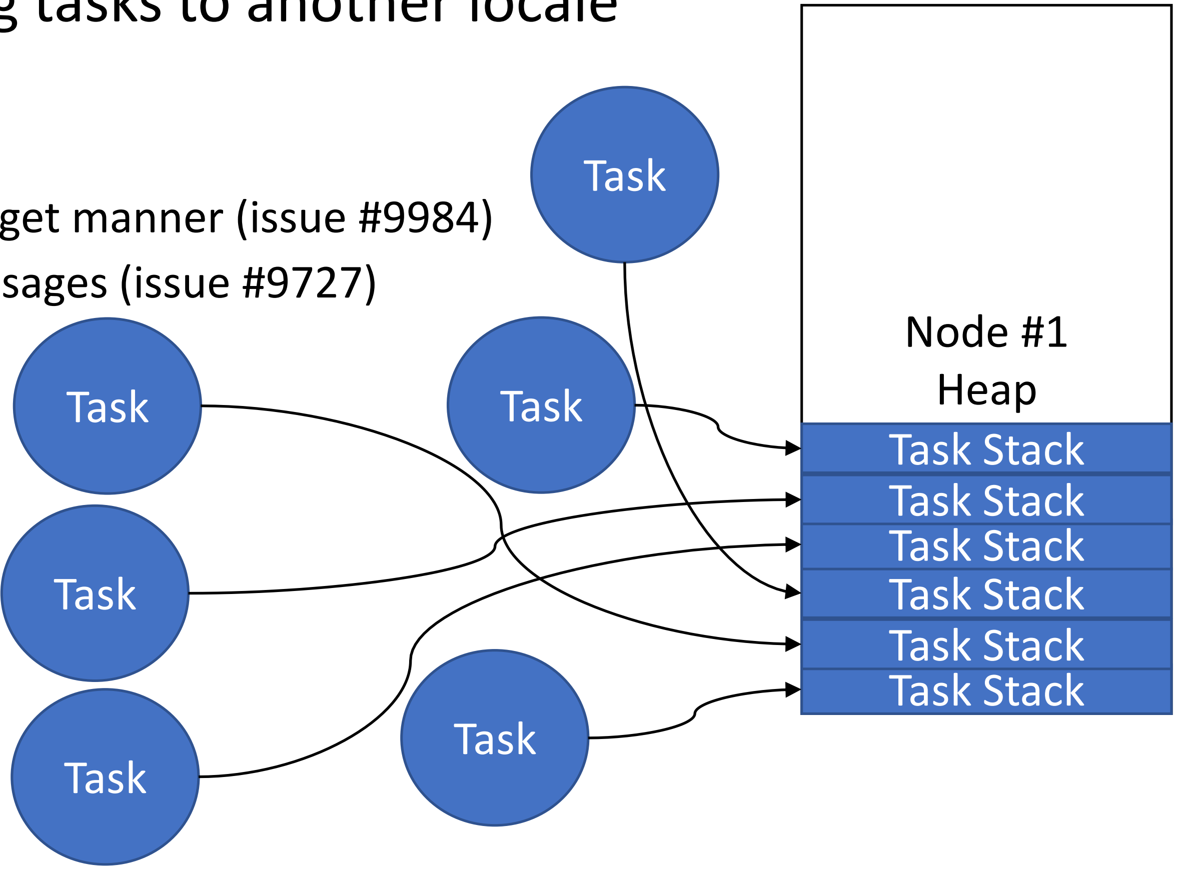
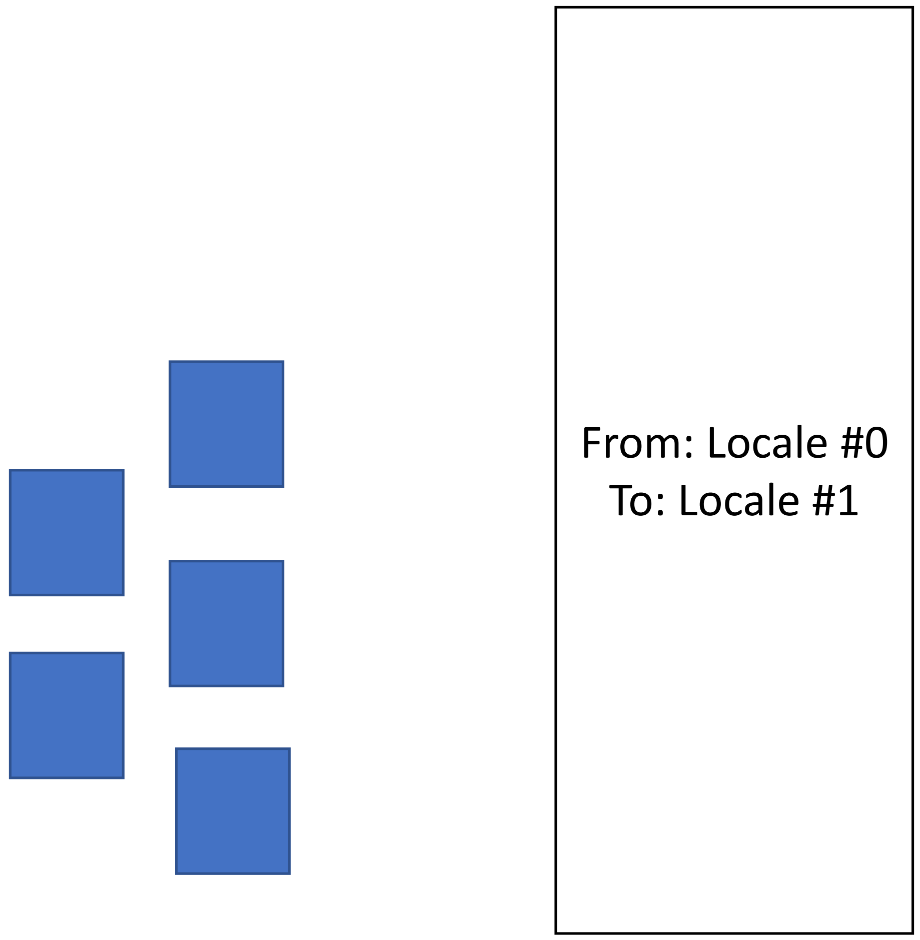
  - Multiple orders of magnitude slower to access than local memory
- "Moving the computation to the data" not always the best solution
  - Using an on statement requires migrating tasks to another locale
    - Can become bottleneck if fine-grained
    - Task creation is relatively expensive
      - Tasks are too large to spawn in a fire-and-forget manner (issue #9984)
      - Migrating tasks require individual active messages (issue #9727)



The Solution

- Coarsen the granularity of the data
  - Buffer units of data to be sent to a locale in *destination buffers*



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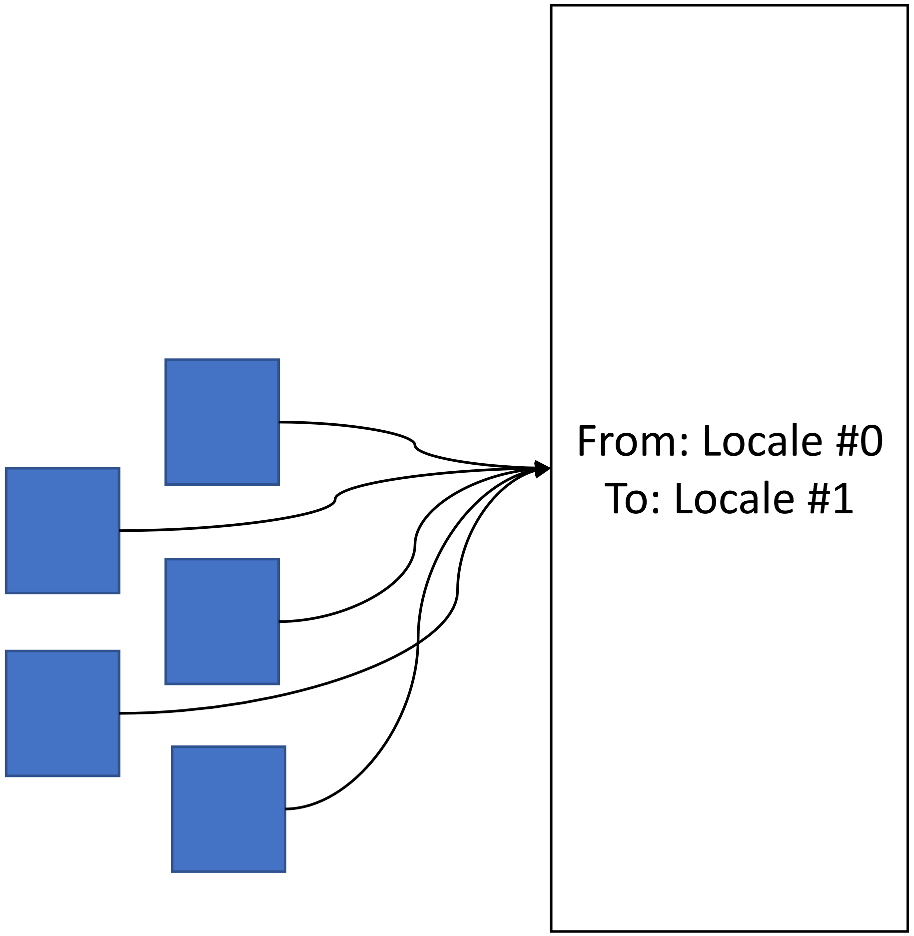

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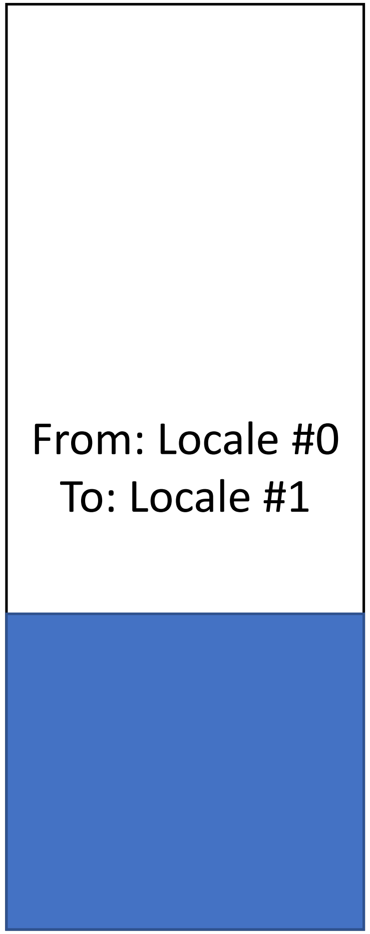
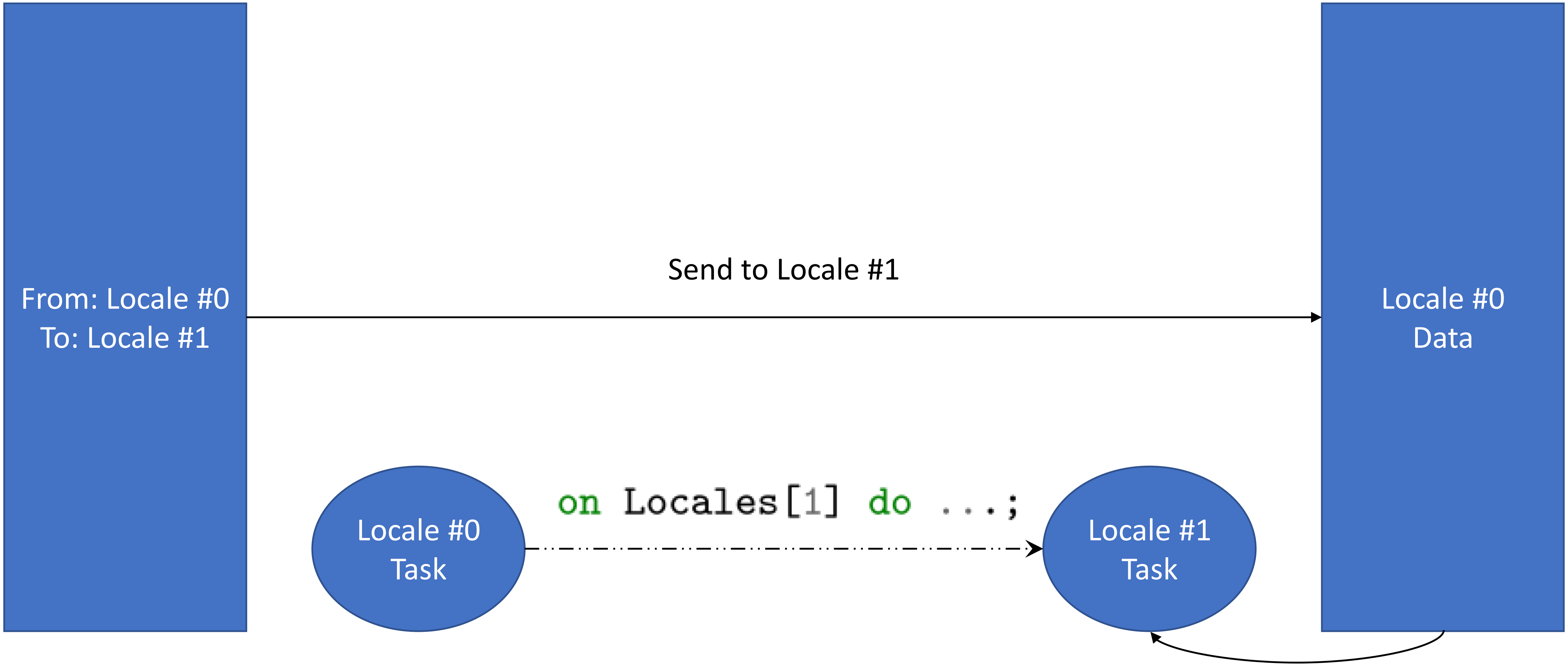


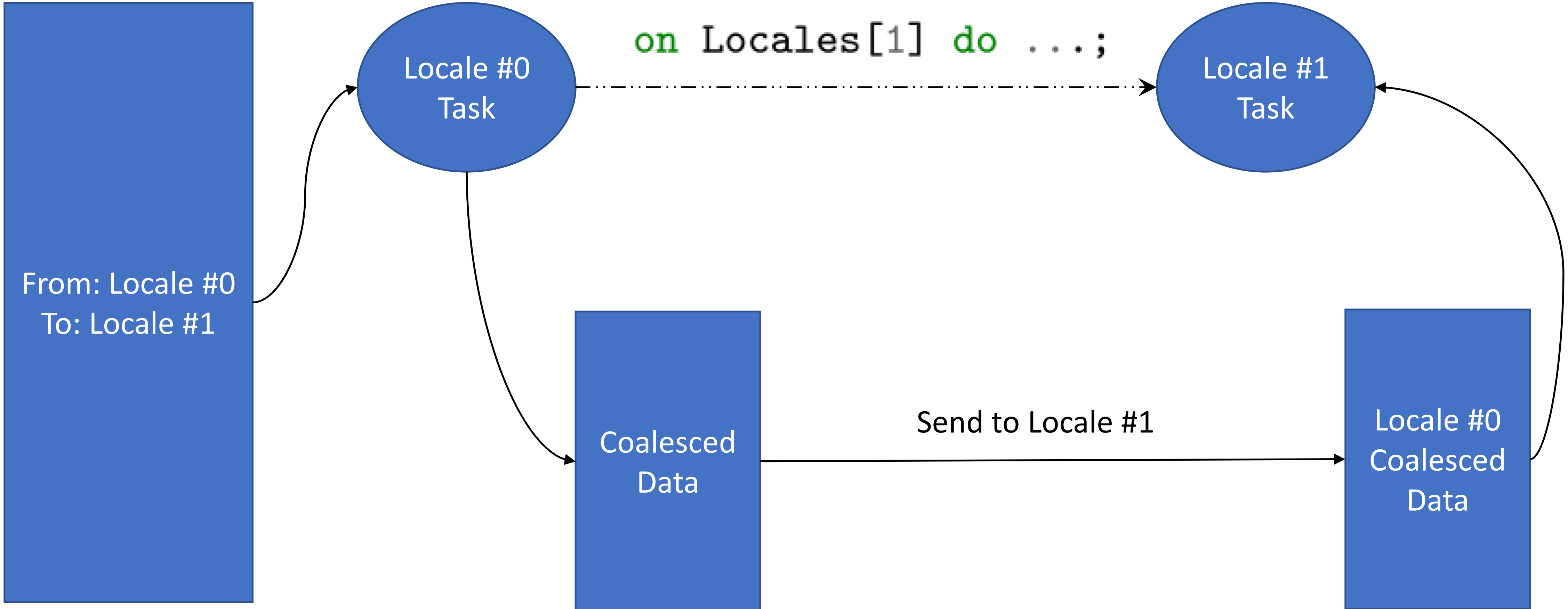
The Solution

- Coarsen the granularity of the data
  - Buffer units of data to be sent to a locale in *destination buffers*
  - When buffer is full, it can be *flushed* to be handled by the user



The Solution

- Coarsen the granularity of the data
  - Buffer units of data to be sent to a locale in *destination buffers*
  - When buffer is full, it can be *flushed* to be handled by the user
  - User can perform *coalescing* to combine aggregated data



The CAL API

Design principles and library semantics

Chapel Aggregation Library (CAL)

- Distributed
  - Privatization makes it possible to use on any locale efficiently
  - Aggregates data in per-locale destination buffers
- Minimal
  - Generic on user data
  - User determines how data is handled
- Parallel-Safe and Parallel-Encouraged
  - Can be called from any task on any locale
  - Provides significant performance improvements
- Chapel Module
  - No run-time nor compiler changes required
  - Written in Chapel, for Chapel

Usage of CAL Initialization

- The ‘Aggregator’ is generic on the type of data it is to aggregate
- Privatization is handled ‘behind-the-scenes’, no extra effort by user

```
var aggregator = new Aggregator(int);
```

Usage of CAL Deinitialization

- The ‘Aggregator’ is record-wrapped
  - No reference counting nor life-time support
  - Cannot *delete* a record
- User must explicitly invoke *destroy* to actually cleanup resources used

```
aggregator.destroy();
```

Usage of CAL
Aggregating Data

- User can *aggregate* data
  - Returns a buffer which must be handled explicitly by user
    - Lack-luster first-class function support prevents automation and optimization
      - Discussed more later

```
for i in 1..N  {
    var buf = aggregator.aggregate(i, Locales[1]);
    if buf != nil {
        handleBuffer(buf, Locales[1]);
    }
}
```

Usage of CAL
Aggregating Data in Parallel

- User can aggregate data from multiple tasks
  - Extremely fast and scales up to maximum parallelism

```
forall i in 1..N  {
   var buf = aggregator.aggregate(i, Locales[1]);
   if buf != nil {
      handleBuffer(buf, Locales[1]);
   }
}
```

Usage of CAL Aggregating Data in Distributed Context

- The Aggregator can be used across multiple locales
  - Uses privatization where each locale has their own local instance
  - **Will not jump to a single locale, <u>all accesses are forwarded to the privatized instance</u> (important!!!)**
- User currently must declare *forall*-intent as *in* to prevent communication
  - Discussed later

```
var A : [someCyclicDom] int;
var B : [someBlockDom] int;
// Wait for all asynchronous tasks to finish
sync forall a in A with (in aggregator) {
   const loc = B[a].locale;
   var buf = aggregator.aggregate(a, loc);
   if buf != nil {
      // Handle buffer asynchronously
      begin handleBuffer(buf, loc);
   }
}
```

Usage of CAL
Flushing Buffers

- User must manually *flush* the buffers when finished
  - Ways to automate this is discussed later
  - For now we use a parallel iterator

```
forall (buf, loc) in aggregator.flush() {
    handleBuffer(buf, loc);
}
```

Example Usage of CAL

Practical example of CAL and performance improvements

Histogram - Naive

- *rindex* is a block distributed array of random indices into *A*
- *A* is a cyclic distributed array of atomic counters
- **Both *rindex* and *A* are distributed differently**

```
forall r in rindex {
    A[r].add(1);
}
```

Histogram - Aggregated

- Coalescing of aggregated data
  - Combine duplicate increments to same index
  - May reduce needed computation needed for destination
  - May reduce size of data being sent
- Benefit of dealing with bulk data
  - Can take extremely large stream of data and process them in windows
    - Might not be possible with entirety of stream

```
// Aggregation Handler
proc handleBuffer(buf : Buffer(int), loc : locale) {
  // Coalescing...
  var counters : [A.domain.localSubdomain(loc)] int(64);
  for idx in buf do counters[idx] += 1;

  // Recycle buffer
  buf.done();

  // Process coalesced data
  on loc {
    // Copy data locally
    const _tmp = counters;
    for (cnt, idx) in zip(_tmp, _tmp.domain) {
      if cnt > 0 {
        A[idx].add(cnt);
      }
    }
  }
}

// Aggregating Indices
var aggregator = new Aggregator(int);

// Aggregate and wait for asynchronous tasks to finish
sync forall r in rindex with (in aggregator) {
  const loc = A[r].locale;
  // If its local, handle it
  if loc == here {
    A[r].add(1);
  } else {
    var buf = aggregator.aggregate(r, loc);
    if buf != nil {
      // Handle buffer asynchronously
      begin handleBuffer(buf, loc);
    }
  }
}

// Flush
forall (buf, loc) in aggregator.flush() {
  handleBuffer(buf, loc);
}
```

Histogram - Aggregated

- Recycling the buffer when finished allows other tasks to use it
  - Safe to call from other locales
    - Not as efficient as calling on host locale
- No longer needed as we already coalesced the data.

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forall (buf, loc) in aggregator.flush() {
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Histogram - Aggregated

- Iterate over local index and coalesced increment count
  - Perform increment to counter that corresponds to local index.

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  }
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// Flush
forall (buf, loc) in aggregator.flush() {
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```

Histogram - Aggregated

- Perform increments that are local immediately
  - Even though overhead is relatively small for aggregating data, nothing beats free
  - Coalescing also is counter-productive here

```
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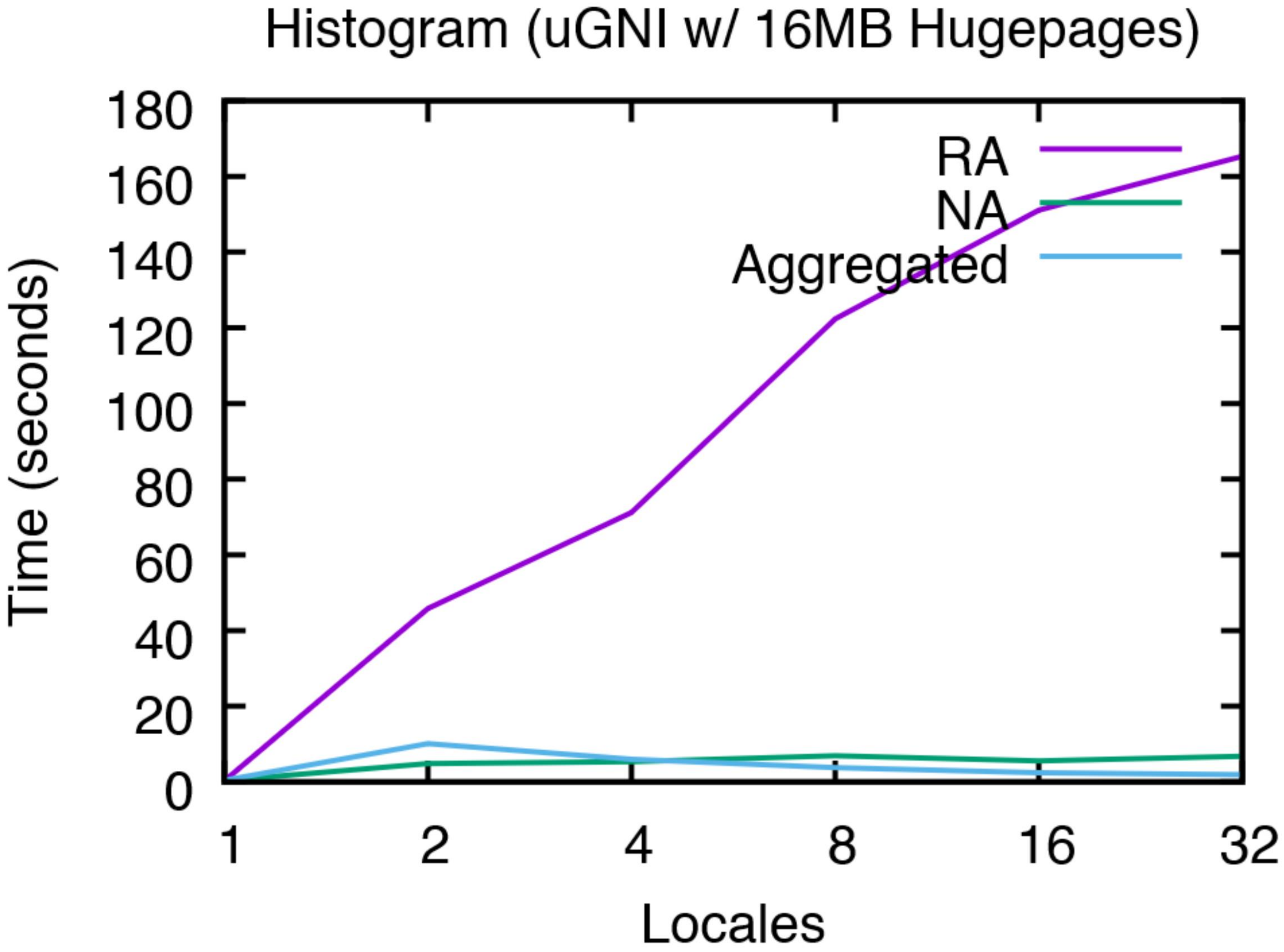
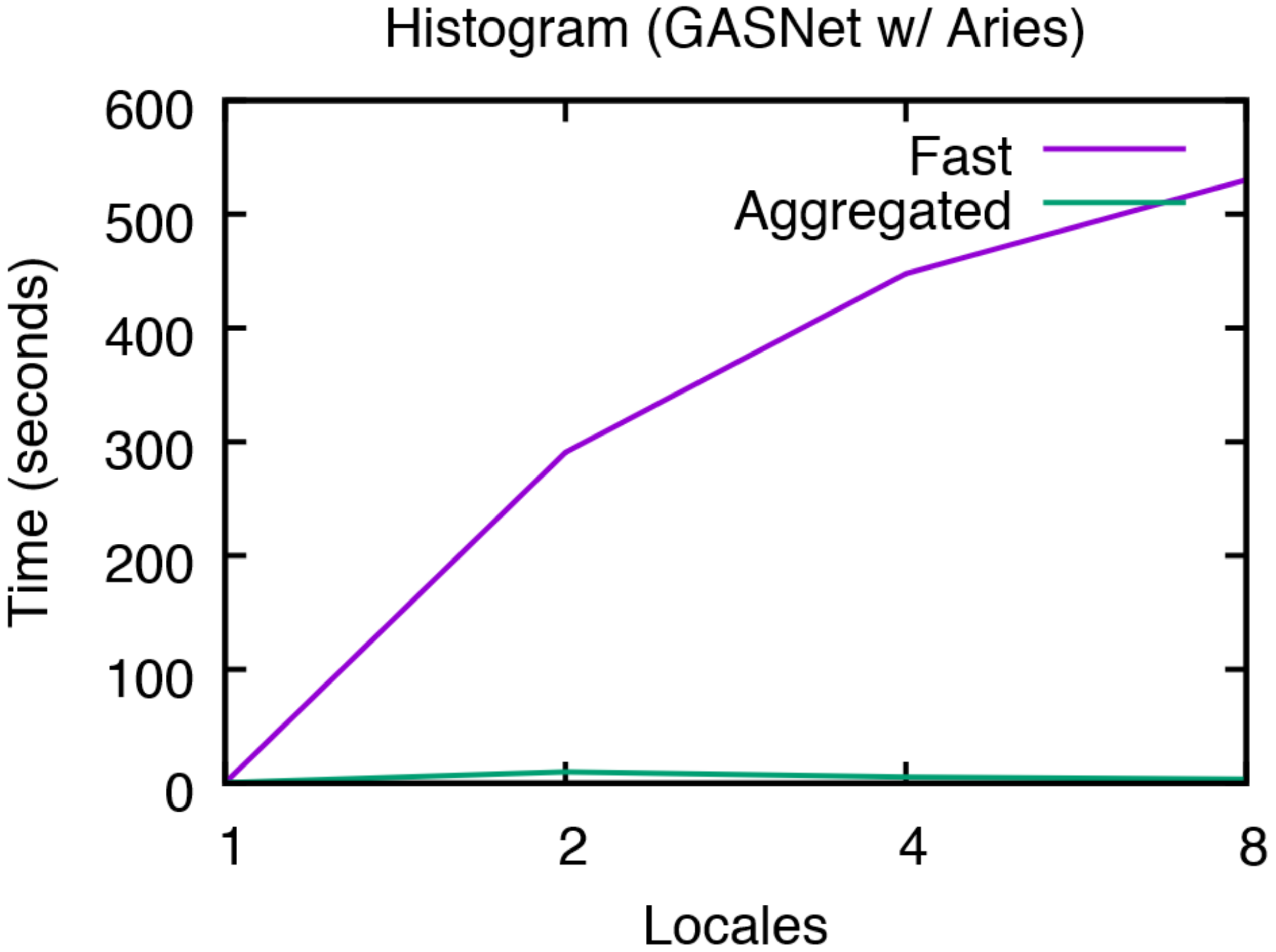

Histogram (uGNI w/ 16MB Hugepages)
Time (seconds)
Locales
RA
NA
Aggregated
0
20
40
60
80
100
120
140
160
180
1
2
4
8
16
32



Histogram (GASNet w/ Aries)
Time (seconds)
Locales
Fast
Aggregated
600
500
400
300
200
100
0
1
2
4
8

Performance Analysis

- Performance under aggregation is the same for both GASNet and uGNI
  - Even though GASNet is significantly slower than uGNI
  - Why? Aggregation reduces the required communication
    - Less PUT and GET
    - Less remote tasks (on-statements)
    - Overall less work for communication layer

Feature Requests

How to make it easier to use CAL

Feature Request
Remote-Value Forwarding on User Types

- Remote-Value Forwarding
  - Compiler-optimization that changes default *forall*-intent as by-value
    - Default is normally by reference where each access is a round-trip to the original locale
  - Would be appreciated for user-defined types (issue #9717)

With Remote-Value Forwarding

```
var A : [someCyclicDom] int;
var B : [someBlockDom] int;
// Wait for all asynchronous tasks to finish
sync forall a in A with (in aggregator) {
   const loc = B[a].locale;
   var buf = aggregator.aggregate(a, loc);
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var A : [someCyclicDom] int;
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   if buf != nil {
      // Handle buffer asynchronously
      begin handleBuffer(buf, loc);
   }
}
```

Benefit to CAL
Remote-Value Forwarding on User Types

- Remove need for user to explicitly define *forall*-intent as *in*
  - Eliminates cases where user forgets to do so leading into bad performance
  - Eliminates cases where user mistakes bad performance for bad library design

Feature Request
Improved First-Class Functions

- First-Class Functions that are similar to inlined iterators
  - Should be efficient to call across multiple locales
    - Accessing 'A' should be remote-value forwarded
- Allow First-Class Functions that access local variables to be returned
  - Copy arguments on stack to the heap if returned and redirect all accesses there
    - Maybe by creating variant of original function object similar to lifetime-checking?
    - Maybe cleaning up heap-allocated data could be done using reference-counting?

```
var handleBuffer = lambda(buf : Buffer(int), loc : locale) {
  begin on loc do [idx in buf] A[idx].add(1);
}
var aggregator = new Aggregator(int, handleBuffer);
sync [idx in indices] aggregator.aggregate(idx, A[idx].locale);
aggregator.flush();
```

Benefit to CAL
Improved First-Class Functions

- Allows user to pass around Aggregator
  - Returning aggregator from a function means returning the handler from a function
- Significantly reduces boilerplate code
  - Makes aggregation quick, easy, and painless
- Allows optimization and automation
  - Flushing of the buffer can be automated and optimized behind-the-scenes

Feature Request
Assigning scheduling priority to tasks

- Not all tasks should be scheduled fairly
  - Some tasks do not need to be scheduled as often as others
  - Some tasks should not be taken into account for calculations
    - I.E *forall* loops for Chapel's standard arrays and distributions
- Categories
  - Background – Tasks that are IO-Bound or are dedicated to book-keeping
  - Normal – Your average task
  - Computational – Tasks that are CPU-bound such as those used in *forall* loops
- Possible approach
  - Implement new scheduler in qthreads as experimental testing ground
    - FIFO tasking layer has no priority, nothing needs to be done for it
    - Massive threads is defunct anyway…

Benefit to CAL
Assigning scheduling priority to tasks

- Single background task per locale that handles flushing buffer
  - Based on rate-of-change heuristic to save time for computational tasks
- Tasks that are aggregating data can be made computational
  - Background tasks can take up less of a time slice from a computational task

```
begin(TaskPriority.Background) {
   while keepAlive {
      doBackgroundWork();
      chpl_task_yield();
   }
}
coforall loc in Locales do on loc {
   forall x in X with (priority TaskPriority.computational) {
       computeWith(x);
   }
}
```

Possible Runtime Integration
Squeezing out more performance

- Aggregation is extremely fast, but…
  - Processing the aggregated data can lead to performance issues
- Add some kind of *routing* of aggregation buffers?
  - Aggregate the aggregation buffers
  - Send buffer to single-hop neighbor
  - Repeat?
- Send data to destination locale
  - Currently have to explicitly retrieve it from source on destination

Extras

Erdős–Rényi – HyperGraph Generation

Hypergraph - Description

- Hypergraph – Consists of *vertices* V and *hyperedges* H
  - Hyperedges represent relationship between 2 <u>or more</u> vertices
    - Such as authors of a paper; vertices are authors, hyperedge is co-authorship on paper
  - A graph is a hypergraph with hyperedges that all have a cardinality of 2
- Dual Hypergraph – Vertices represent relationship between <u>2 or more</u> hyperedges
  - If a hyperedge contains a vertex, then that vertex contains that hyperedge
    - Bidirectional mapping of vertices and hyperedges
- Hypergraph generation – Synthetically create hypergraph based on information

Erdős–Rényi – Naïve

- A *Vertex* is an object with an adjacency list of indices that map to *Edge* objects
- A *Edge* is an object with an adjacency list of indices that map to *Vertex* objects
- *vertices* is a distributed array of *Vertex* objects
- *edges* is a distributed array of *Edge* objects
- *verticesRNG* and *edgesRNG* are pre-computed random indices for *vertices* and *edges* respectively

```
// Iterate over distributed array of pre-computed random numbers
forall (randVertex, randEdge) in zip(verticesRNG, edgesRNG) {
   on vertices[randVertex] do vertices[randVertex].addEdge(randEdge);
   on edges[randEdge] do edges[randEdge].addVertex(randVertex);
}
```

Erdős–Rényi – Aggregated (Idealized)

```
enum Inclusion { Vertex, Edge }
type dataType = (int, int, Inclusion);
proc handleBuffer(buf : Buffer(dataType), loc : locale) {
   on loc {
       forall (src, dest, opType) in buf {
          select opType {
             when Inclusion.Vertex do vertices[src].addEdge(dest);
             when Inclusion.Edge do edges[src].addVertex(dest);
          }
       }
   }
   buf.done();
}

var aggregator = new Aggregator(dataType, handleBuffer);
sync forall (vRNG, eRNG) in zip(verticesRNG, edgesRNG) {
      const vData = (vertex, edge, Inclusion.Vertex);
      const eData = (edge, vertex, Inclusion.Edge);
      const vLoc = vertices[vertex].locale;
      const eLoc = edges[edge].locale;
      aggregator.aggregate(vData, vLoc);
      aggregator.aggregate(eData, eLoc);
}
aggregator.flush();
```