Performance Optimizations

Chapel Team, Cray Inc.
Chapel version 1.12
October 1st, 2015
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Outline

- STREAM Case Study
- Parallel Array Initialization Optimization
- Array Allocation Improvement
- Running Task Count Improvements
- Muxed Thread Limit Improvement
- Impact of Hugepages
- Optimizing Task Counters
- Stream Performance Summary
- Locality Optimizations
- Performance Improvements Summary
STREAM Case Study
STREAM Case Study: Background

- Previous releases focused on single-locale performance
  - More and more, Chapel is becoming competitive with C/C++

- For this release we shifted our focus to multi-locale
  - Using STREAM as a case study to motivate optimizations
    - a simple benchmark, but important to get right

- Several important optimizations resulted from this work:
  - Parallelized array initialization
  - Switched from calloc() to malloc() for array allocation
  - Corrected running task counts
  - Removed thread limit for muxed
  - Investigated hugepage issues
  - Optimized task counters
**STREAM: a trivial parallel computation**

**Given:** $m$-element vectors $A$, $B$, $C$

**Compute:** $\forall i \in 1..m, A_i = B_i + \alpha \cdot C_i$

**In pictures:**

```
A = B + \alpha \cdot C
```
STREAM: a trivial parallel computation

**Given:** $m$-element vectors $A$, $B$, $C$

**Compute:** $\forall i \in 1..m$, $A_i = B_i + \alpha \cdot C_i$

In pictures, in parallel (distributed memory multicore):

```
A = = = = = = = = = =
B + + + + + + + + +
C ⋅ ⋅ ⋅ ⋅ ⋅ ⋅ ⋅ ⋅ ⋅
α  ⬤  ⬤  ⬤  ⬤  ⬤  ⬤  ⬤  ⬤  ⬤  ⬤
```
```c
#include <hpcc.h>
#elif defined _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 (%d).\n", VectorSize );
            fclose( outFile );
        }
        return 1;
    }

    #ifdef _OPENMP
    #pragma omp parallel for
    #endif
    for (j=0; j< VectorSize; j++) {
        b[j] = 2.0;
        c[j] = 0.0;
    }

    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);
```
Chapel Stream EP (1.11 version)

```
coforall loc in Locales do on loc {
    local {
        var A, B, C: [1..m] elemType;
        initVectors(B, C);
        startTimer();

        forall (a, b, c) in zip(A, B, C) do // parallel vector iteration
            a = b + alpha * c;

        stopTimer();
    }
}
```

- Written in traditional SPMD style (not elegant Chapel)
- Spawns one task per locale (outside of timed region)
- 1.11 version used `local` block to help squash communication
Global STREAM: Chapel

**Chapel Global Stream**

```chapel
const ProblemSpace = {1..m}
dmapped Block({1..m}); // create distributed domain

var A, B, C: [ProblemSpace] elemType;
initVectors(B, C);

startTimer();

forall (a, b, c) in zip(A, B, C) do // parallel vector iteration
  a = b + alpha * c;

stopTimer();
```

**Elegant Chapel version**
- Uses distributed (global) arrays
- Spawning tasks on other locales happens within timed region
STREAM: Chapel

Our main performance goals for 1.12:
- Improve the compiler, runtime, and modules such that:
  - stream-ep performs as well as the reference
  - global stream is competitive with the reference
- Improve compiler locality analysis and optimizations such that:
  - the local block in stream-ep can be removed
STREAM: Motivation

- Relatively simple and straightforward benchmark
  - Easy for us to debug and find performance issues
  - Has a minimal amount of communication
    - makes it easy to isolate other performance and scaling bottlenecks
  - Stream-inspired optimizations should improve most benchmarks
  - Serves as a proxy for embarrassingly/pleasingly parallel computations

- Affinity is crucial for getting good performance

- Utilizes all cores and significant amounts of memory
  - Should help identify weak links in tasking, memory, and comm layers

- Global version demonstrates productivity of domain maps
  - Competitive results will help abate long-term performance concerns
    - i.e. show that productivity and performance are not mutually exclusive
STREAM: Testing Configuration

- **Run on a Cray XC40:**
  - 24 core (48 HT) IvyBridge Processor (2 numa domains)
  - 128 GB RAM per node
  - GCC 4.9.2

- **Studied cross product of tasking, memory, comm layers**
  - To make isolating performance issues easier
  - To ensure that there are no glaring issues with any given layer

- **Test Results**
  - Will show several configurations compared to reference
    - and impact of individual changes
  - Most slides will show stream-ep vs. reference (GB/s per node)
    - will do a comparison of global stream at the end
**STREAM: Initial Performance**

- In general we were just over 2x worse than reference
- Slightly worse for muxed and fifo

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Parallel Array Initialization Optimization
Parallel Initialization: Background

- Uninitialized variables are assigned a default value
  
  ```
  var i: int; // default initialized to 0
  var A: [1..10] int; // each element default initialized to 0
  ```

- Array initialization has traditionally been serial
  - Initialization is typically responsible for “first-touch”
    - incorrect first-touch results in poor affinity, which can hurt performance

- Need a principled way to get good first-touch
  - Short term: we want to default to some sort of parallel initialization
  - Long term: domain map author should specify parallel initialization
    - permits parallelization strategy to match parallel iterators
    - requires finalizing and implementing our constructor proposal
    - also want to permit users to ‘noinit’ arrays
Parallel Initialization: This Effort

● **Determine when parallel initialization is appropriate**
  ● Consistent to assume that *most* arrays will be used in parallel
    ● other operations are parallel by default (promotion, reductions, etc.)
  ● However, parallel initialization is not always the right choice
    ● e.g. code with many small arrays (especially if constructed in a loop)

● **Heuristic: Parallel initialize numeric arrays > 2MB**
  ● Initial attempts at heuristics were naïve
    ● tried to parallel initialize all arrays, then tried several unreliable heuristics
  ● Moved to experimentally determining a good size
    ● 2MB is good for 2 core laptop, 8 core desktop, 24 core XC, 240 core KNC
  ● Decided to only parallel initialize numeric arrays
    ● serious performance regressions for arrays of arrays
    ● will be addressed in future releases, but was not high priority now
    ● stepping stone will be to enable for arrays of plain old data (POD) types
Parallel Initialization: Impact

- Improvements for several benchmarks

- Regressions for benchmarks testing serial array access
  - understood, and acceptable (not representative of “real” code)
Parallel Initialization: Stream Impact

- **Substantial performance improvements**
  - for all tasking layers
  - for gasnet-mpi
  - for most memory layers

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Parallel Initialization: Stream Impact

- **Substantial performance improvements**
  - for all tasking layers
  - for gasnet-mpi
  - for most memory layers (except tcmalloc)

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Array Allocation Improvement
Array Allocation: Background

**Background:** Noticed that tcmalloc still had bad first-touch
- Discovered that array allocation was being done with `calloc()`
- tcmalloc always uses `memset()` with `calloc()`, which touches pages
  - dlmalloc and cstdlib check if `mmap()` zeros pages and avoid `memset()`

**This Effort:** Switch to using `malloc()` instead of `calloc()`
- There was no reason for us to be using `calloc()`
  - we initialize arrays in the modules after allocation
  - `calloc()` was inadvertently introduced in early hierarchical locales work
Array Allocation: Stream Impact

- **Substantial performance improvements**
  - for single locale tcmalloc

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Substantial performance improvements

- for single locale tcmalloc
- (overall, single locale was still slightly behind reference)

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Running Task Count Improvements
Running Task Count: Background

**Background:** Discovered locale 0 was mostly unused
- non-blocking on-stmts were being counted as local running tasks
- as was the task waiting for a coforall/cobegin to complete
- Iterators select degree of parallelism based on running task count
- incorrect running task count led to iterators creating too few tasks

```plaintext
coforall loc in Locales do on loc {
   // running task count on locale 0 was numLocales+1 here, rather than 1
}
```

**This Effort:** Improve accuracy of running task count
- Stop counting non-blocking on-stmts as tasks
- Stop counting the task waiting for a coforall/cobegin to finish

```plaintext
coforall loc in Locales do on loc {
   // now, running task count is 1 on all locales
}
```
Running Task Count: Impact

- Several performance improvements
  - Larger values are better

HPCC: FFT Perf (Gflop/s) - n=2^{20}

HPCC: HPL HPCC Version Perf (Gflop/s) - n=22k, nb=200
Running Task Count: Stream Impact

- **Substantial performance improvements**
  - qthreads is on par with reference!
  - gasnet-mpi 1- and 16-locale are on par with reference!
  - fifo was close to reference

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Running Task Count: Stream Impact

- **Substantial performance improvements**
  - qthreads is on par with reference!
  - gasnet-mpi 1- and 16-locale are on par with reference!
  - fifo was close to reference (muxed did not change)

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Muxed Thread Limit Improvement
Muxed Thread Limit

**Background:** Discovered muxed was only using 16/24 cores

- Outdated code limited muxed to max of 16 hardware threads
  - muxed was originally tuned for Gemini and SSCA#2 in HPCS days
- Hardware and muxed configuration have changed since then
  - hard-coding this thread limit unnecessary and undesirable
- Missed this in previous releases since our machines only had 16 cores

**This Effort:** Remove limit on number of hardware threads

- Default is now the number of physical cores
  - can be changed by user up to a comm layer limit (as with qthreads/fifo)
Muxed Thread Limit: Impact

- Several performance improvements
  - Larger values are better

![Graphs showing performance improvements over time](image-url)

- HPCC: HPL HPCC Version Perf (Gflop/s) - n=22k, nb=200
- HPCC: STREAM-EP Perf (GB/s) - n=5,723,827,200
Muxed Thread Limit: Stream Impact

- **Substantial performance improvements**
  - 1-locale muxed is really close to reference
  - `qthreads` (our default for 1.12) has better support for affinity and pinning
  - 16-locale muxed was slightly better than before

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## Muxed Thread Limit: Stream Impact

- **Substantial performance improvements**
  - 1-locale muxed is really close to reference
  - qthreads (our default for 1.12) has better support for affinity and pinning
  - 16-locale muxed was slightly better than before (16-locale ugni still bad)

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Impact of Hugepages
Hugepages: Background

**Background:** ugni and gasnet-aries use hugepages

- Cray Gemini/Aries NICs must register (pin) memory to access it
  - gasnet-aries always registers, ugni only registers when numLocales > 1
- Registration is page-based, NIC has limited number of entries
  - registering significant memory requires huge pages
- Currently Chapel registers the entire heap and data segment
  - unfortunately, registration touches pages causing bad first-touch

**This Effort:** Investigate solutions for bad first-touch with ugni

- Work to resolve this issue is underway
  - but did not make it into the 1.12 release
- We will show the performance of that work for stream
  - to see the impact of later optimizations
- Did not investigate gasnet-aries yet
  - suspect memory registration also leads to bad first-touch
Hugepages: Stream Impact

Reminder:  This work did not make it into 1.12

- Substantial performance improvements
  - for 16-locale ugni (still off from reference though)

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Optimizing Task Counters
Optimizing Task Counters: Background

- Chapel has support for network-based atomics
  - Chosen globally using CHPL_NETWORK_ATOMICS
    - changes default type for all atomic variables
  - Availability depends on hardware/environment
    - currently available only for comm=ugni

- Internally, Chapel uses atomics for:
  - the running task counter on each locale
  - tracking the # of completed tasks for a parallel construct (‘endcounts’)
    - begin, cobegin, and coforall
Optimizing Task Counters: Background

- Historically, task counters used default atomic type
  
  ```
  // Processor or network atomic, depending on CHPL_NETWORK_ATOMICS
  var runningTaskCounter: atomic int;
  // Ditto for compiler-generated endcounts for sync, cobegin, coforall statements…
  ```

- A parallel construct’s endcount may be provably local
  
  ```
  coforall i in 1..10 {...}  // lack of on-stmt means it’s local
  cobegin {...}
  ```

- Processor atomics are much faster for local operations
Optimizing Task Counters: This Effort

● **Force use of processor atomics for running task counter**
  ● It is a per-locale counter that is always accessed locally
  ● Current method of forcing processor atomics not intended for users
    ● future work to provide a user-facing mechanism
    ● possibly repurposing the “local” keyword

● **Have compiler choose atomic type for endcounts**
  ● Use processor atomics for local `cobegin` and `coforall` statements
    ● i.e. blocking parallel constructs that do not have an `on`-statement

● **Note that these changes are invisible to users**
  ● Contained within compiler and internal modules
Optimizing Task Counters: Impact

- Positive impact for multi-locale programs
  - For CHPL_COMM=ugni
  - Larger values are better

---

**HPCC: RA-atomics Perf (GUPS) - n=2^33, N_U=10M**

- ra-atomics GUPS (gnu+ugni-qthreads)
- ra-atomics GUPS (gnu+ugni-muxed)
- ra-atomics GUPS (gnu+gasnet-aries)

**HPCC: Promoted STREAM Perf (GB/s) - n=5,723,827,200**

- promoted stream GB/s (gnu+gasnet-aries)
- promoted stream GB/s (gnu+ugni-qthreads)
- promoted stream GB/s (gnu+ugni-muxed)
Optimizing Task Counters: Stream Impact

- **Substantial performance improvements**
  - **Note:** these numbers are with the hugepage workaround
  - 16-locale ugni is on par with 1-locale – qthreads on par with reference

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Stream Performance Summary
Stream Performance Summary

**Summary of Improvements:**

- Parallelized array initialization
- Switched to `malloc()` for array allocation
- Corrected running task count
- Removed thread limit for muxed
- Investigated hugepage issues
- Optimized task counters
Stream EP

coforall loc in Locales do on loc {
  local {
    var A, B, C: [1..m] elemType;
    initVectors(B, C);
    forall (a, b, c) in zip(A, B, C) do
      a = b + alpha * c;
  }
}

Global Stream

const ProblemSpace = {1..m} dmapped ...;

var A, B, C: [ProblemSpace] elemType;
initVectors(B, C);
forall (a, b, c) in zip(A, B, C) do
  a = b + alpha * c;

● Our main performance goals for 1.12:
  ● Improve the compiler, runtime, and modules such that:
    □ stream-ep performs as well as the reference
    □ global stream is competitive with the reference
  ● Improve compiler locality analysis and optimizations such that:
    □ the local block in stream-ep can be removed
Stream Performance Summary

Stream EP Performance:

- Blue configurations perform as well as the reference!
  - Still have a little work to do for ugni
    - last remaining issue is understood and already being worked on
  - Gasnet-aries still has first-touch problems
    - not a high priority (only used if building from source on a Cray)

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Reference: 74 GB/s 74 GB/s 74 GB/s

Global Stream Performance:

- Blue configurations perform close or as well as reference!
  - No overhead for 1 locale
  - Slight (3%) overhead for 16 locales
    - most likely because remote task creation is inside timed section
    - could also mean that our block distribution could use some tuning
Our main performance goals for 1.12:

- Improve the compiler, runtime, and modules such that:
  - stream-ep performs as well as the reference
  - global stream is competitive with the reference

- Improve compiler locality analysis and optimizations such that:
  - the local block in stream-ep can be removed
Locality Optimizations
Locality optimizations: Background

**STREAM-EP in 1.11:**

```plaintext
coforall loc in Locales do on loc {
    local { // Permits compiler to squash overheads related to wide pointers
        var A, B, C: [1..m] elemType;
        initVectors(B, C);

        forall (a, b, c) in zip(A, B, C) do
            a = b + alpha * c;
    }
}
```

**Goal:** get rid of the local block
- Cumbersome language feature in general
- Compiler **should** be able to eliminate all overhead in this case
  - code within local block can be trivially seen to be local

**Wide pointers are the main source of overhead**
Locality optimizations: Background

- Wide pointers represent potentially remote data

```c
typedef struct {
    int localeID;  // where this object lives
    Foo addr;     // pointer to data
} wide_Foo;      // wide pointer for class Foo
```

- Use runtime GETs and PUTs to read/write data
  - Will short-circuit if data is local

- Significant source of overhead
  - Some overhead for runtime calls
  - Potential for communication thwarts back-end compiler optimizations
Locality optimizations: Background

- ‘chpl’ has traditionally introduced wide pointers liberally
  - Simple implementation
  - Easier to ensure program correctness
  - Unnecessary overhead, often for cases that seem easy

- Particularly bad for arrays
  - Wide pointer overhead for every array access
  - Reason STREAM-EP had a local block
    ```
    local { // Squashes overhead for wide pointers
      forall (a, b, c) in zip(A, B, C) do
        a = b + alpha * c;
    }
    ```
Locality optimizations: Improving the compiler

- Eventually, hope to remove all local blocks
  - Used in other benchmarks like FFT, LULESH, etc.
  - Also used inside standard distributions like Block

- Many cases dependent on compiler improvements
  - For other cases, we intend to move to data-centric locality assertions
    - e.g., “access the local slice of this array”

- First step: improve part of compiler architecture
  - Make it easier to write new optimizations
  - Reduce complexity of existing analysis
Locality optimizations: Improving the compiler

- 1.11 had two compiler passes to manage wide pointers

# Wide Pointers

- All data considered local, initially

Pass #1: Insert wide pointers for **all** data

Resulting program state is overly conservative, expensive

Pass #2: Perform analysis and undo “widening” from Pass #1

Final output
Locality optimizations: Improving the compiler

**Problem:** Easy for wide pointers to stick around
- First pass inserts many unnecessary wide pointers
- Second pass was often not smart enough to remove them

**Solution:** Merge two passes into one
- Only insert wide pointers when necessary
- Fewer variables will be wide pointers by default

# Wide Pointers

- All data considered local

**New Pass:** Analyze AST and insert wide pointers

Final output
Locality optimizations: Improving the compiler

- **New pass is less complex**
  - Less code (by several hundred lines)
  - Only handles cases that involve wide pointers
  - Easy for developers to see when/why a wide pointer was inserted

- **Easier to add new optimizations**
  - Can manipulate AST without completely restarting analysis
  - More utility functions for developers

- **Should be able to improve compiler analysis more quickly**
Locality optimizations: Better analysis

● **Problem:** Fields in aggregate types are wide pointers
  ● For a simpler code-generation implementation

● Tuples are represented as records in AST
  ● Fields “x1”, “x2”, etc. will be wide pointers

● Stream’s arrays are eventually wrapped in a tuple
  ● Due to implementation of zip
    
    ```python
    forall (a, b, c) in zip(A, B, C) do ...
    ```

● Those arrays are then referred to using wide pointers
  ● Adds significant overhead on every read/write on array
Locality optimizations: Better analysis

- **Solution:** Compiler should not widen every field by default

- Only insert a wide pointer…
  - when a field is visible to another locale
  - if a field is assigned to by another wide pointer

- Reduces overhead for compiler-inserted classes/records
Locality optimizations: Impact

- STREAM-EP on 16-node XC40
  - For gasnet-mpi

![Graph showing GB/s per node comparison before and after locality optimizations. The graph compares performance with and without a local block.](image-url)
Locality optimizations: Impact

Promoted op= Time (no-local)

Scalar Multiplication 2D Array Execution Time

1D Array Parallel Iteration
Locality optimizations: Next Steps

● **Goal:** Eliminate use of local block in other benchmarks
  - HPCC FFT
  - LULESH
  - HPL

● Continue improving compiler’s locality analysis

● Provide data-centric locality support
  - Repurpose “local” keyword in variable/type/indexing contexts
  - See CHIUW 2015 talk [Data-Centric Locality in Chapel](#) for details
Stream Locality Summary

Stream EP

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Stream Locality Summary

Our main performance goals for 1.12:

- Improve the compiler, runtime, and modules such that:
  - stream-ep performs as well as the reference
  - global stream is competitive with the reference

- Improve compiler locality analysis and optimizations such that:
  - the `local` block in stream-ep can be removed
  
  Note: removing it also enabled other code cleanups not shown above
Performance Improvements Summary
Performance: Summary

- **This release we focused on multi-locale performance**
  - We used steam as a case study to motivate optimizations
  - We achieved our performance goals for stream
    - resulting in our first truly competitive and scalable benchmark
    - as well as significant improvements for other many other benchmarks

- **Previous slides have shown performance at 16 locales**

- **Following slides will show performance up to 256 locales**
  - Run on 1-256 nodes of a Cray XC40:
    - 32-core (64 HT) Haswell Processors
    - 128 GB RAM per node
    - GCC 5.1.0
Performance: Summary

- Performance trends are the same at higher node counts
  - Performance has more than doubled since last release
  - EP is on par with the reference
  - Global is also very competitive (spinning up parallelism is scaling)

![Performance of STREAM](image-url)

- Performance has more than doubled since last release
- EP is on par with the reference
- Global is also very competitive (spinning up parallelism is scaling)
Performance: Summary

- **Performance trends are the same at higher node counts**
  - Performance has more than doubled since last release
  - EP is on par with the reference
  - Global is also very competitive (spinning up parallelism is scaling)

![](chart.png)

**Efficiency of STREAM**
(GASNet/mpi+qthreads)

- **Locales**
  - 1.11 Global
  - 1.11 EP
  - 1.12 Global
  - 1.12 EP

% Efficiency (scaled from 0.374s)

- 100%
- 80%
- 60%
- 40%
- 20%
- 0%
Performance: Next Steps

● **Complete remaining work for stream**
  ● Resolve ugni hugepage performance issue
    ● and possibly gasnet-aries as well
  ● Determine if global stream performance can be improved
    ● particularly as node counts grow
  ● Compare/improve other variants of writing stream
    ● e.g., promoted operator version; domain-based iteration + indexing

● **Optimize more complicated multi-locale benchmarks**
  ● Likely starting with RA, other HPCC benchmarks, and ISx
    ● possibly working towards an HPCC entry for SC16

● **Continue improving compiler locality optimizations**
  ● Guided by removing “local” blocks from other benchmarks
Appendix: Larger Stream Scalability Graph Images
Performance: Summary

Performance of STREAM
(GASNet/mpi+qthreads)

GB/s

Locales
Reference  I.12 EP  I.12 Global
I.11 EP  I.11 Global
Performance: Summary

Efficiency of STREAM
(GASNet/mpi+qthreads)

% Efficiency
(scaled from 0.374s)

Locales
1.11 Global
1.11 EP
1.12 Global
1.12 EP

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