Ongoing Efforts

Chapel Team, Cray Inc.
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Outline

- **Compiler**
  - Improving Array Memory Management
  - Error Handling
  - Stack Allocate Argument Bundles
  - Partial Reductions
- **Modules**
  - Chapel on Intel Xeon Phi “Knights Landing” (KNL)
  - DefaultRectangular Multi-DData
  - Mason: A Package Manager for Chapel
- **Applications**
  - Machine Learning

Ongoing Compiler Efforts

Improving Array Memory Management

Arrays: Outline

- **What is the problem?**
  - Array memory management was incorrect and slow
- **Why do we have this problem?**
  - Original semantics of arrays required reference counting
- **How did we address the problem?**
  - Language changes
  - Leveraging improved semantics
- **What is the result of this work?**
  - Huge reduction in leaks, varied performance impact

Arrays: Background: The Problem

- **Array memory management has been problematic**
  - memory leaks
  - performance overhead
- **Largest source of memory leaks**
  - distributed array leaks account for most leaked data
  - privatized objects are leaked
  - distributions, distributed domains leak as well
- **Significant overhead reduces performance**
  - Array memory management overheads can be surprising:

    ```
    var size = A.domain.size; // changes reference counts!
    ```
  - Benchmarks spend significant time handling array reference counting
    - Have supported a 'noRefCount' setting to measure/reduce impact
    - Sometimes dramatic, but guaranteed arrays will be leaked

Arrays: Background: How did we get here?

- **Arrays are implemented to keep arrays alive**
  - when an array slice outlives the original array
  - when arrays are used in begin statements

```
proc run() {
  var A:[1..100] int;
  begin {
    computeWith(A);
  }
} // local variables normally destroyed here
```

- **And at the same time, to minimize array copies**
- **But…**
  - Implementation erred on keeping arrays alive to the point of leaking
  - Reference counting approach was expensive and overly conservative
  - Language definition did not clearly specify array return behavior

Arrays: This Effort

- **To solve these problems we**
  - altered the behavior of returning arrays
  - leveraged this change to eliminate reference counting
- **Lexical scoping eliminates need for reference counting**
  - arrays should be freed when they go out of scope
  - begin statements need not prevent arrays from being freed
  - array slices need not prevent arrays from being freed
- **Re-implemented array, domain, distribution types to:**
  - remove array reference counting
  - free distributed objects
  - rely on fewer special cases in the compiler

Array Challenges: Tuple Improvements

- **Tuple semantics have never been well-defined**
  - a known gap in the language specification
  - CHIP-6 proposed one strategy, but was never finalized or acted upon
  - things have worked "well enough" for this not to receive more attention
- **The array effort ran afoul of issues with tuples**
- **Led us to rework the tuple implementation**
  - Guiding principal: 1-element tuples behave similarly to plain elements
  - implementation is now more direct and straightforward

Array Challenges: Reference Types

- **Compiler has longstanding issues with representing 'ref's**
  - inconsistent representations
  - incorrectly identified
- **The array effort ran into challenges related to this**
- **Motivated a new approach: separate ref-ness from type**
  - new 'Qualifier' IR component
    - ref, const-ref, value, param, unknown, …
    - references now correctly identified, no longer in the type
- **Still need to propagate this change through the compiler**
  - working our way backwards through the passes
- **A positive change independent of arrays work**
  - fewer record copies in some cases
  - addresses long-standing pain-point for compiler developers

Arrays: This Effort: Language Changes

- **Arrays are now destroyed when they go out of scope**
  - begin statements and array slices no longer affect array lifetime
- **Arrays return by value by default**
  - ref and const ref return intent request alternative behavior

Arrays: Now Destroyed When Out Of Scope

- **Using arrays past their scope is now a user error:**

```
proc badBegin() {
  var A: [1..10000] int;
  begin {
    A += 1;
  }
  // Error: A destroyed here at function end, but the begin could still be using it!
}
```

- **Using a slice after original array destroyed now an error:**

```
proc badSlice() {
  var A: [1..10000] int;
  var slice => A[1..1000];
  return slice;
  // A destroyed here at end of the function, but the returned slice refers to it!
}
```

Arrays: Now Return by Value By Default

- **Now the act of returning an array makes a copy:**

```
var A: [1..4] int;
proc f() {
  return A;
}
ref B = f();
B = 1;
writeln(a);
// outputs 1 1 1 1 historically
// outputs 0 0 0 0 after this work
```

- **Old behavior available with ref return intent:**

```
proc f() ref {
  return A;
}
```

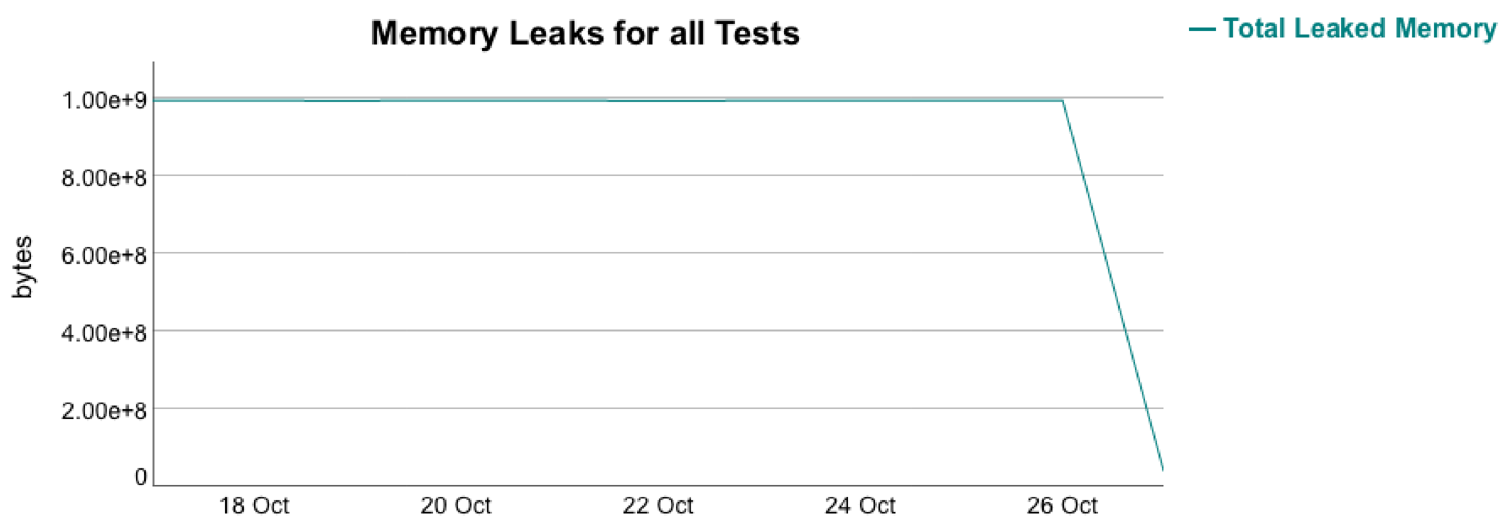
Arrays: Status

Status:

- Array improvements merged to master on Oct 26th
  - testing reasonably clean, particularly given magnitude of changes
  - graphs on following slides are taken from the next day's results
- Had hoped to include this in 1.14, but did not feel sufficiently confident
  - it's a significant change
  - even if it could have been ready in time, wanted to live with it for awhile
- Closes biggest memory leak sources
- Generally improves performance

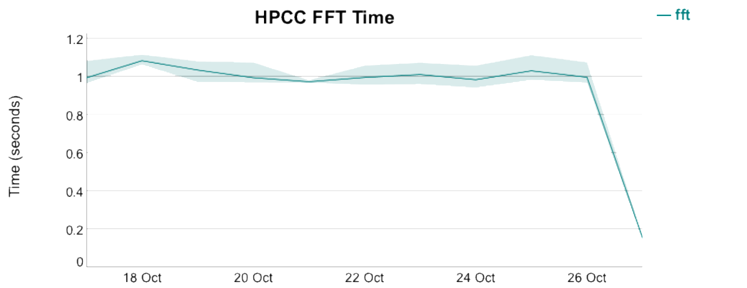
Arrays: Impact on Leaks

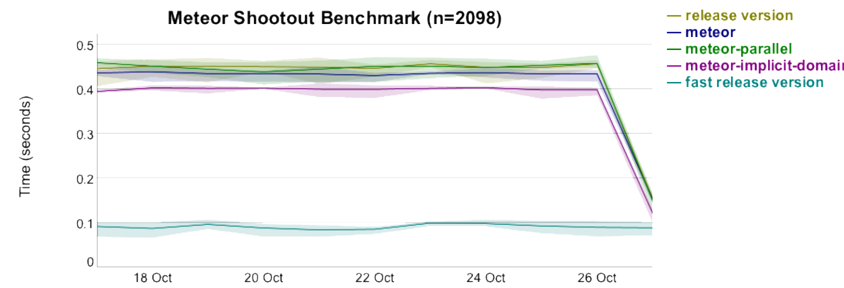
- **Memory leaks were dramatically reduced**
  - Biggest source of memory leaks closed
    - PTRANS benchmark went from leaking 800MB to 0 bytes
  - Distributed arrays no longer leak
    - With the exception of ReplicatedDist (default constructor issue)

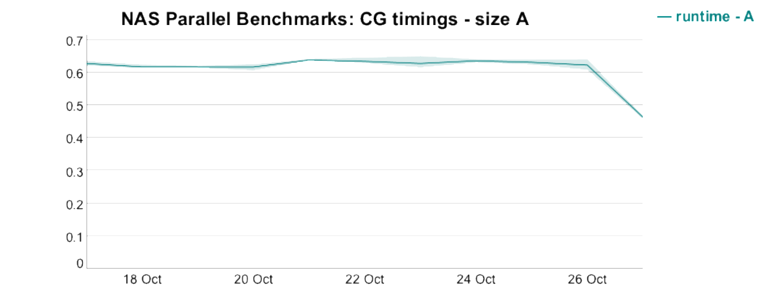


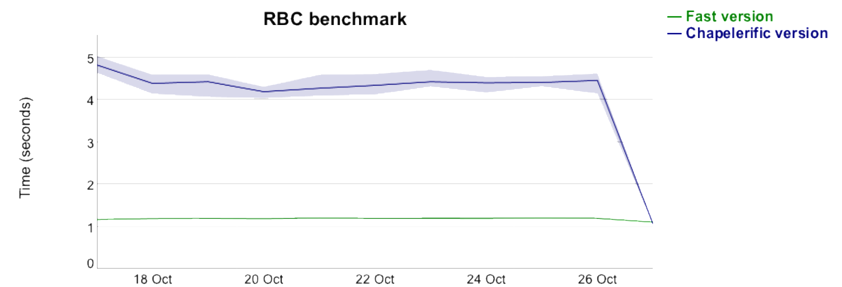
Arrays: Impact on Performance

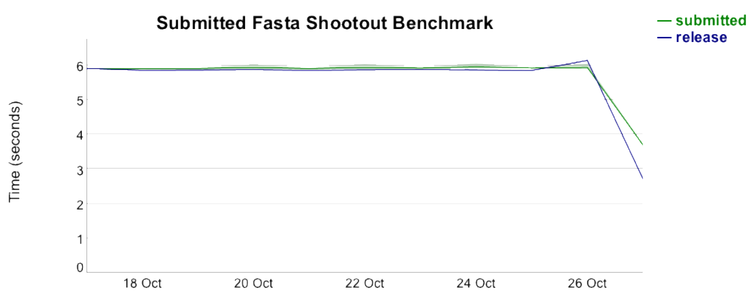
- Substantial single-locale performance improvements

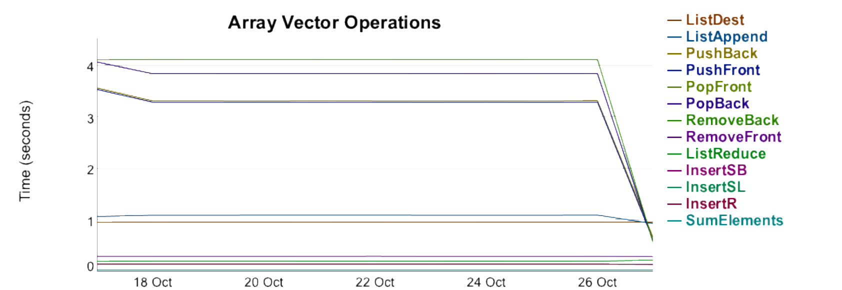






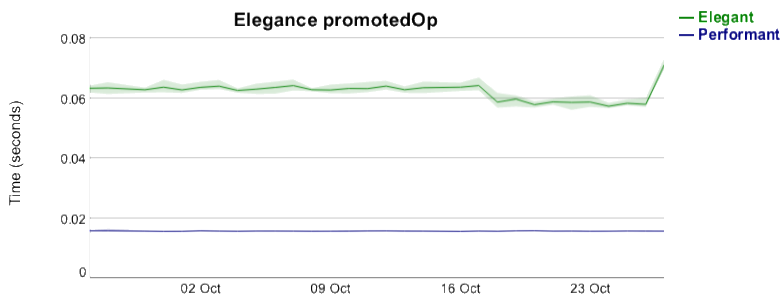




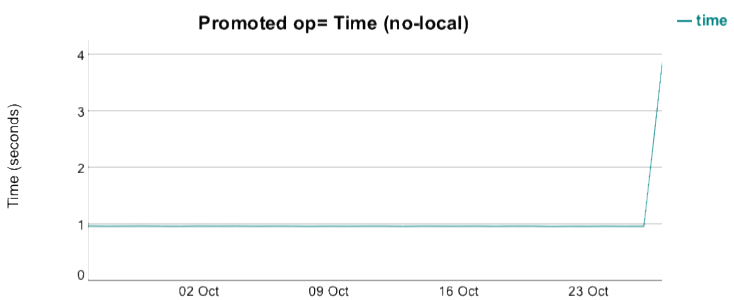


Arrays: Impact on Performance

- **Some minor single-locale performance regressions**

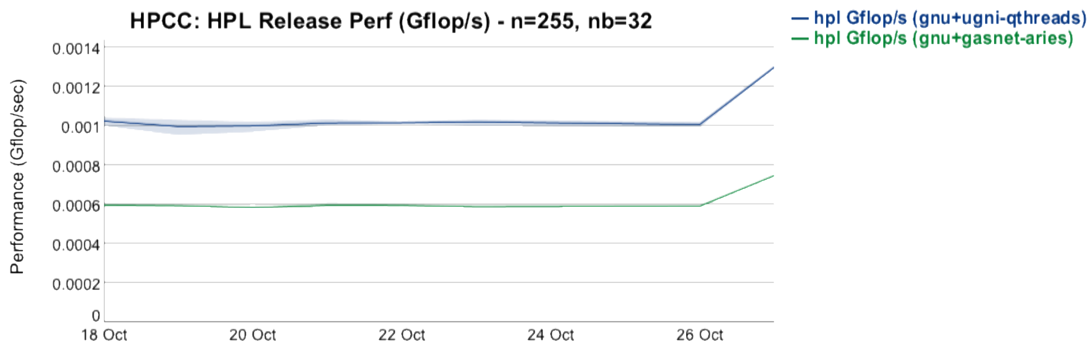


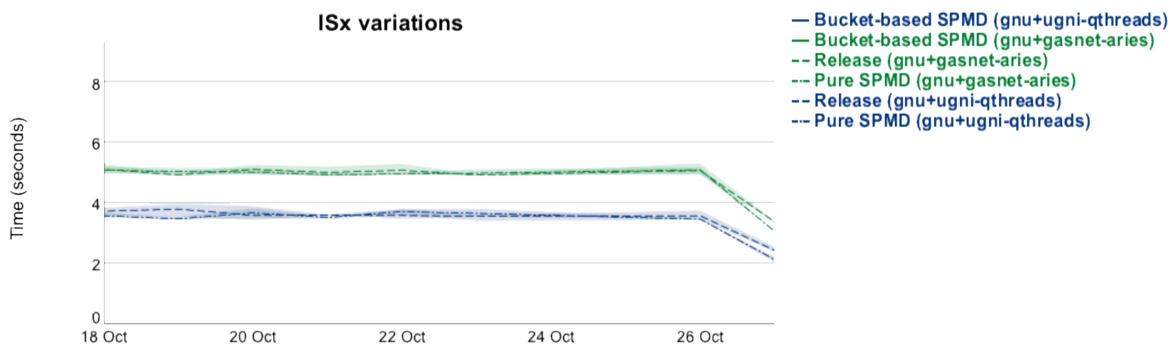
- **Only one major single-locale performance regression**
  - Have not had time to investigate yet



Arrays: Impact on Performance

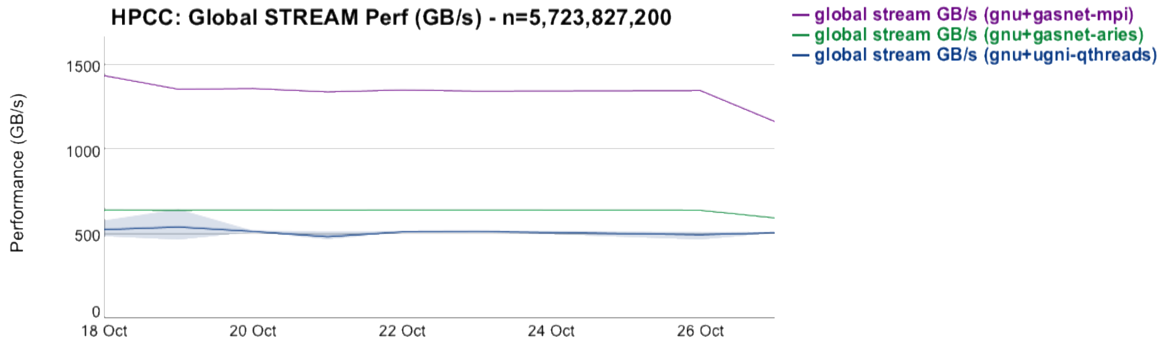
- Some decent multi-locale performance improvements

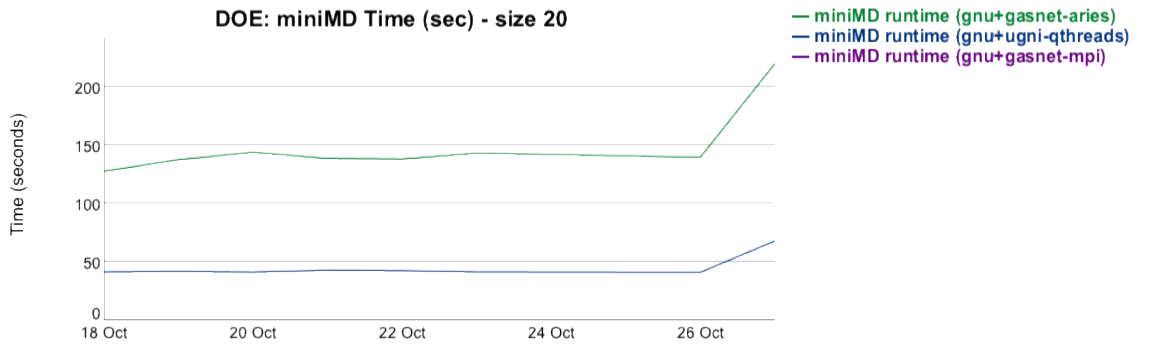




Arrays: Impact on Performance

- **A few multi-locale performance regressions**
  - Root cause still needs to be investigated





Arrays: Next Steps

Next Steps:

- Investigate and resolve performance regressions
  - not surprising that there were a few regressions
  - code was just merged, need some time to investigate
- Close remaining memory leaks
  - issue with generic member variables causing leak with ReplicatedDist
  - undiagnosed leak observed in some applications
  - close non-array-based memory leaks
- Optimize away deep array copies when possible
  - e.g., returning local arrays and assigning result
  - extend this optimization to other record types as well (e.g., ‘bigint’)
- Update language specification to describe:
  - when record/array copies occur
  - tuple semantics in more detail
  - function return is normally by-value

Error Handling

Error Handling: Background

- **Chapel lacks a general strategy for handling errors**
  - Current approaches: `halt()` and "error" out arguments
  - These are insufficient moving forward
- **First cut at an improved design was modeled after Swift**

```
proc canThrowErrors() throws { ... }
do {
  try canThrowErrors();
  try! canThrowErrors(); // will halt on failure
} catch {
  writeln("first call failed!");
}
```

  - All calls that might throw must be marked with `try`
    - Makes control flow clear with only local information
    - Feedback was that this is too verbose
  - Early feedback from users, developers wanted a way to elide try
    - e.g., lack of try results in halt-like behavior

Error Handling: This Effort

- **Improve the syntax and semantics**
  - Streamline for usability
  - Maintain clarity of control flow
- **Decide on an implementation approach**
- **Design document can be found in CHIP #8**

Error Handling: syntax and semantics

- **Mark error-throwing procedures with `throws`**
- **Throwing calls must be enclosed by `try` or `try!`**
  - Eliminated `do`
  - Defined for single statement and { } blocks
  - Both will attempt to match errors to a `catch` block
- **If a matching `catch` is not found:**
  - `try` propagates the error
    - To an outer `try`, or out of the procedure (which must throw)
  - `try!` is similar but halts instead of propagating

```
try {
  canThrowErrors();          // handled by catch on error
  try canThrowErrors();      // propagated to outer try, which goes to catch
  try! canThrowErrors();     // halts on error
} catch {
  writeln("first call failed!");
}
```

Error Handling: default and strict mode

- **Tension between convenience and correctness**
- **Default mode**
  - If a throwing procedure is not enclosed with `try`:
    - Halt if that procedure throws an error
- **Strict mode**
  - If a throwing procedure is not enclosed with `try`:
    - Raise a compiler error
- **To start, toggle between modes with a compiler flag**
  - Expect to include a more fine-grained approach in the future
    - Per-module or per-function

Error Handling: errors as classes

- **Long-term goal of supporting many types as errors**
  - classes, records, enums, unions, tagged unions, etc.
- **To start, all errors must be classes**
  - Implementation convenience
  - Base class `Error` will be provided
- **`catch` blocks match against an `Error` at runtime**

```
try {
  trickyOperation(badArg);
} catch IllegalArgumentError {   // matches IllegalArgumentError, subtypes
  writeln("illegal argument!");
} catch {                        // catch-all block, prevents auto-propagation
  writeln("unknown error!");
}
```

Error Handling: implementation approach

- **Compiler translates into 'out' error arguments**

```
// Example: function signatures
proc canThrowErrors() throws { ... }
// translates into
proc canThrowErrors (out _e_out) { ... }
```

```
// Example: try-throws
proc caller() throws {
  try canThrowErrors();
}
// translates into
proc caller(out _e_out) {
  var _e: Error;
  canThrowErrors(_e);
  if _e then
    _e_out = _e;
}
```

```
// Example: try!
proc handler() {
  try! canThrowErrors();
}
// translates into
proc handler() {
  var _e: Error;
  canThrowErrors(_e);
  if _e then
    halt(_e.message);
}
```

Error Handling: implementation approach

```
// Example: try-catch
proc catch() {
  try {
    canThrowErrors();
  } catch {
    writeln("error occurred");
  }
}
// translates into
proc catch() {
  var _e: Error;
  canThrowErrors(_e);
  if _e then
    writeln("error occurred");
}
```

```
// Example: try-catch-throws
proc attempt() throws {
  try {
    canThrowErrors();
  } catch e: SomeError {
    writeln(e.message);
  }
}
// translates into
proc attempt(out _e_out: Error) {
  var _e: Error;
  canThrowErrors(_e);
  if _e: SomeError then
    writeln(_e.message);
      else if _e then
    _e_out = _e;
}
```

Error Handling: runtime errors

- **C runtime is independent of Chapel error handling**
  - Modify runtime to return error codes
  - Chapel wrapper translates runtime error codes to throws

```
// Example: in module code
proc chpl_here_alloc(size: int): c_void_ptr throws {
  extern proc chpl_mem_alloc(size: int) : c_void_ptr; // runtime proc
  const p = chpl_mem_alloc(size); // always returns
  if p == c_nil then              // runtime says allocation failed
    throw new OutOfMemoryError();
  return p;
}
```

- **More involved implementation**
  - Will not be included in initial version

Error Handling: error cleanup

- **`defer`, Swift's cleanup construct**
  - Runs whenever the enclosing scope exits
  - Cleanup code is local to initializing code
  - Useful outside of error handling
- **Chapel will adopt something similar to `defer`**

```
proc caller() throws {
  try {
    var a = allocateBigObject();
    defer {
      delete a;
    }
    canThrowErrors(a);
  }
}
```

- **More involved implementation**
  - Will not be included in initial version

Error Handling: Status and Next Steps

Status:

- Design is hosted on the Github repository as CHIP 8
  - Advertised to the community and solicited feedback

Next Steps:

- Implement the design in the compiler
- Release the feature to users in Chapel 1.15.0

Stack Allocate Argument Bundles

Stack Allocate Argument Bundles

Background: on/begin/cobegin/coforall create argument bundles

- these argument bundles are heap-allocated in the generated code
- heap allocation can be a significant source of overhead

This Effort: compiler generates code to stack-allocate bundles

- the runtime can copy to a heap-allocated region when appropriate
  - in fact, the runtime already does so in many cases because the generated code might free the bundle before it is used
- runtime can identify when a bundle could be destroyed before use

Impact: Observed 10-20% speedups for LULESH and MiniMD

Next Steps: Complete the change

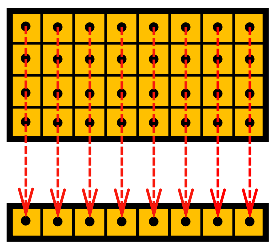
- nontrivial effort since it touches all tasking and communication layers

Partial Reductions

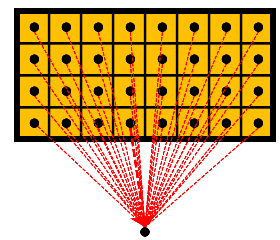
Partial Reductions: Background

- *Partial* reductions reduce over subset of array dimensions

ex. partial reduction over columns produces a row



cf. *full* reduction produces a single element



- Partial reductions are not available in Chapel at present
  - Important for many algorithms, particularly matrix-vector multiplication
  - Can be written manually, but typically at greater expense

Partial Reductions: This Effort – Goals

Design and implement partial reductions

- **Candidate syntax:**

"this is a partial reduction over 2nd dimension"

```
var Q = + reduce only(2) [(i,j) in MatDom] (A(i,j) * P(j));
```

partial reduction over 1st and 3rd dimensions produces a single column for a 3D array

```
const C = + reduce only(1,3) myCube;
```

Partial Reductions: This Effort – Prototypes

Developed templates for compiler to apply

- "Got a partial reduction? Replace it with this piece of code."
- Implemented partial + reductions of arrays, over a single dimension
- Relies on proposed support within array's domain map
  - **proc** dsiPartialDomain() → domain with remaining dimension(s)
  - **iter** dsiPartialThese() → how to iterate over remaining dimension(s)
  - domain map gets to decide which locales are involved, in what order, etc.

- **Basic template**

*// implements: result = + **reduce only**(2) myArray;*

```
forall partIdx in myArray.domain.dsiPartialDomain(exceptDim=2)
do result[partIdx] =
     + reduce myArray.dsiPartialThese(2,partIdx);
```

- **"Bulk" template**
  - communicate per-locale results in bulk to improve performance
  - interface and performance need further development

Partial Reductions: Next Steps

- **Have compiler invoke templates**
  - implement parser changes
  - convert reduction operation into templates
  - avoid creating temporary result if user copies it into an array anyway
- **Generalize to arbitrary expressions, multiple dimensions**
- **Consider bringing ZPL flood/grid dimensions to Chapel**
  - Useful in reduction scenarios for both users and implementers
- **Improve performance**
  - finalize "bulk" template

Ongoing Module Efforts

Chapel on Intel Xeon Phi “Knights Landing” (KNL)

Chapel on KNL: Background

- KNL is a many-core platform (60+ cores).
- Access both to external memory and to on-chip high-bandwidth multichannel DRAM (MCDRAM).
- Presents an opportunity to broaden Chapel’s NUMA support in preparation for more complex architectures.

Chapel on KNL: This Effort

- **We examined MCDRAM performance characteristics**
  - Experimented with real Chapel code using and not using MCDRAM
- **For many Chapel codes, MCDRAM makes little difference**
- **On two key benchmarks, saw a significant difference**
  - Streaming: ~50% speedup on tested Chapel code
  - Random-access: ~20% slowdown on tested Chapel code
- **As a result, we changed our strategy**
  - We were planning to allow users to ask for "fast" memory
  - Now we plan to split this into two kinds of "fast"
    - Streaming
    - Random Access
  - Similar to the way the *madvise()* system call works on pages

Chapel on KNL: Status and Next Steps

Status:

- Have prototype locale model from previous release cycle
- Gained better understanding of KNL performance characteristics
- Changed plans regarding mechanism of MCDRAM support

Next Steps:

- Leverage previous and new insights to enhance NUMA support
- Target KNL in a way that can be used for future architectures
  - KNL Locale Model
  - “Get streaming memory” or “get random-access memory”
- Take advantage of latest Qthreads, with better KNL support
- Work on vectorization improvements/optimizations
  - Also explore potential KNL-specific optimizations

DefaultRectangular Multi-DData

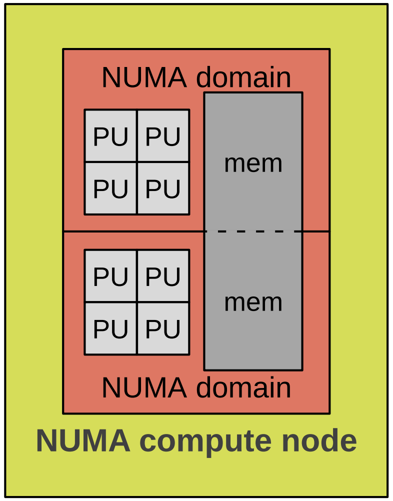
DefaultRectangular Multi-DData: Effort

- **Background:** 'numa' locale model doesn't perform as desired
  - DefaultRectangular domain and arrays lack sublocale optimizations
  - domain places tasks as desired (subject to tasking layer limitations)
  - but arrays have 1 *ddata* data block per node, not explicitly placed
    - thus: no reliable data/task affinity

- **This Effort:** Localize data as DefaultRect domain does tasks

```
forall … do <something> ;

coforall … on … {      // across numa sublocales
  coforall … on … {    // across PUs within subloc
    for … do <part of something in subloc's mem>
  }
}
```



  - implement *multi-ddata* arrays: 1 ddata per sublocale
    - used whenever locales have sublocales (e.g. numa)
    - set NUMA/sublocale affinity of ddata blocks via OS

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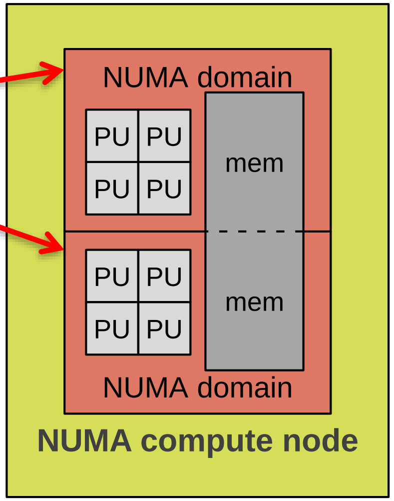

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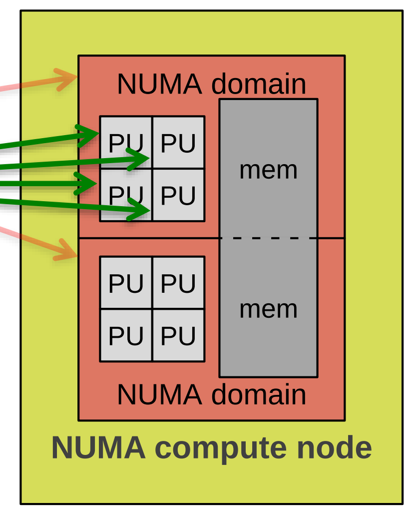

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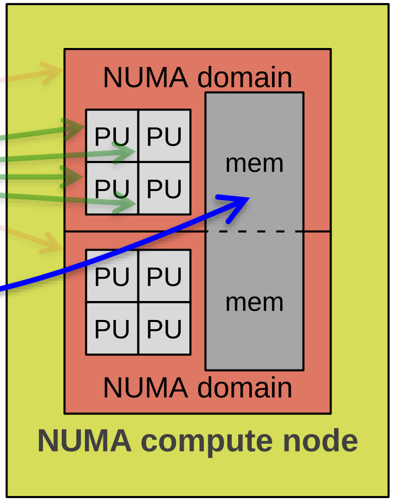

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DefaultRectangular Multi-DData: Status

History & Status:

- did not make as much progress as hoped and planned this cycle
- currently working on more principled array index → ddata mapping
  - old: leftmost dim with range >= #sublocales, must divide evenly
  - new: same, but without "divide evenly", ±1 index val per ddata block
    (exactly matches task distribution)
- array remote-access data (RAD) opt, bulk I/O, bulk transfer not done

Next Steps:

- finish new index → ddata mapping
- finish RADopt, bulk I/O, bulk transfer
- runtime tasking: implement task placement in qthreads tasking layer
- memory management:
  - numa-awareness in runtime memory layer(s)
  - on Cray X* systems, integrate with use of hugepages

Mason: A Package Manager for Chapel

Mason: Background

- **Currently packages are bundled with the rest of Chapel**
- **A lot of drawbacks and few benefits:**
  - Developers must sign a CLA
  - Code must be under a compatible license
  - Chapel core team needs to be involved
  - Packages must serve a wide audience
  - Bound to Chapel's six month release cycle
- **Not ideal for a healthy Chapel ecosystem**

Mason: This Effort

- **Designed a package management system for Chapel**
  - Package manager
  - Build system
  - Package registry
- **Trying to avoid reinventing the wheel**
  - Shares traits with Rust's Cargo and homebrew
- **Design document can be found in [CHIP #9]**

Mason: Sample Workflow

- **Mason is a command line tool for package management**
  - Also manages project builds
- **Getting started**
  - Initialize the project directory

    ```
    mason new [project name] ...
    ```
  - For project name foo, this produces:

    ```
    Foo/
      Mason.toml
      src/
        Foo.chpl
    ```
  - Write your project code
  - Build your project

    ```
    mason build
    ```
    - In our example, this will compile `Foo.chpl`

Mason: Sample Workflow

- **Dependency management**
  - Add or remove dependencies

    `mason add [package] [version]`

    `mason rm [package]`
  - Pulled in and included by `mason build`
  - Dependency code is downloaded to a common pool of packages
- **Project manifest file**
  - `Mason.toml`
  - Tracks dependencies
    - Edited automatically by mason
    - May be edited manually
  - Stores project metadata
    - Must be edited manually (name, version, authors, license, etc.)

```
[package]
name = "hello_world"
version = "0.1.0"
authors = ["Bradford Chamberlain <brad@chamberlain.com>"]
license = "Apache-2.0"

[dependencies]
Curl = "1.0.0"
```

Mason: Package Registry

- **Implementation**
  - Github repository of package manifest files
  - Identical to the one in the project, plus a source url field
  - Publish a package by submitting a pull request
- **Issues**
  - Namespacing
    - First-come, first-served
  - Versioning
    - Semantic versioning
  - Integrity
    - Travis CI suite
    - Review board
  - Licensing
    - SPDX

```
[package]
name = "hello_world"
version = "0.1.0"
authors = ["Brad Chamberlain <brad@chamberlain.com>"]
license = "Apache-2.0"
source = { git = "https://github.com/bradcray/hello_world", tag = "0.1.0" }

[dependencies]
Curl = "1.0.0"
```

Mason: Implementation Details

- **Lock file**
  - `Mason.lock`
  - "Locks in" a build configuration from the manifest
    - Serialized DAG of all dependencies
    - Points to specific Git SHAs
  - Ensures repeatable builds on other machines
  - After editing a manifest, generate a new lock
    - `mason update`
- **Syncing commands**
  - mason is a pipeline
    - source → manifest → lock → dependency code
  - When mason commands are run, keep them in sync
    - ex. `mason add`
    - triggers `mason update`, downloaded dependencies

Mason: Status and Next Steps

Status:

- Design is hosted on the Github repository as CHIP 9
  - Advertised to the community and asked for feedback

Next Steps:

- Implement `mason` in Chapel
- Build and release the first version

Ongoing Application Efforts

Machine Learning

Machine Learning: Background

- **Deep learning frameworks have various limitations/issues**
  - Frameworks support narrow range of parallel & memory architectures
    - Limited by the choice of parallel libraries used in implementation
  - Supporting more architectures requires combining many libraries
    - All with their own syntax and semantics
    - Introduces complexity and burdens framework development
  - Typically written in C/C++
    - Often requiring interface with more productive languages, like Python or R

Machine Learning: Background

- **Chapel provides solutions to current issues**
  - Natively supports a wide range of parallel & memory architectures
    - The list continues to grow
  - Parallelism expressed under the same syntax and semantics
  - Chapel is productive and performant
    - And can still provide interoperate with other languages

- **Machine learning is a good use-case for Chapel analytics**
  - Deep learning identified as good area to focus within machine learning
    - Incredible amount of traction in research & industry
    - Often requires significant computational resources
    - Consequently, scalable implementations are necessary

Machine Learning: This Effort

- **Built some toy ML codes**
  - Helped develop an understanding of the basics
  - Helped determine what building blocks are needed in Chapel for ML

- **Identified necessity for high-level linear algebra interface**

- **Created a linear algebra module: LinearAlgebra.chpl**
  - Provides high-level syntax for linear algebra routines
    - Similar in nature to Python's NumPy or Matlab's linear algebra interface
  - Built on top of BLAS / LAPACK
    - Users can swap out implementations as needed
    - Could some day be entirely Chapel, as performance permits

Machine Learning: Impact

- **Examples of LinearAlgebra interface:**
  - Matrix-matrix / matrix-vector multiplication: `dot(A, B)`
  - Matrix transpose: `A.T()`
  - Matrix inverse: `inverse(A)`
  - Identity matrix: `eye({1..10, 1..10})`

- **Some toy ML codes built:**
  - Normal Equation
  - Gradient Descent
  - Neural network
    - Creates an N-layer network with any number of neurons per layer
    - Supports stochastic gradient descent with backpropagation

Machine Learning: Status and Next Steps

Status: Progress towards machine learning in Chapel

Next Steps: Continue to explore ML in Chapel

- Publish Linear Algebra module in 1.15
  - Add additional routines
  - Documentation
  - Integrate BLAS/LAPACK installation with Chapel build system
- Combine existing toy codes into a simple ML framework
- Ramp up toy code implementations, and compare to other frameworks
  - Explore optimizations and parallel implementations
- Work towards a deep learning application
  - Identify or create a benchmark to measure Chapel's performance
  - Collaborate with researchers on real-world applications

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