Language Improvements

Chapel Team, Cray Inc.
Chapel version 1.18
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Outline: Major Language Improvements

- **Initializers**

- **Delete-Free Programming**
  - Background
  - Language Design
  - Status in 1.18
  - Next Steps

- **Shape Preservation for Loop Expressions and Promotions**

- **Task-Private Variables**

- **Override Checking**

- **Namespace / Resolution Improvements**

- **Enumerated Type Improvements**
Outline: Other Language Improvements

- **Type Constraint Improvements**
  - Sidebar: Reduced Compilation Time
- **UTF-8 String Support**
- **Param Renaming of Extern/Export Procedures**
- **Generic Array Return Types**
- **Improvements to Method Forwarding**
- **‘in’ Intent Improvements**
- **Dynamic Dispatch with Variable Arguments**
- **Improvements to Arrays, Domains, and Domain Maps**
  - Array-as-Vector Improvements
  - Sorting Sparse Indices for LayoutCS
Initializers
Initializers: Background and This Effort

Background:

- Have been developing initializers to replace constructors
  - Provide significantly more control over classes and records
  - Extensive progress made over last few releases
- As of Chapel 1.17...
  - Core of initializers proposal was implemented
  - A number of bugs remained
  - Constructors were still the default

This Effort:

- Fixed many bugs
- Improved error messages
- Initializers enabled by default, deprecated constructors
Initializers: Bug Fixes

- **Prioritized user-submitted bugs**
  - For example...
    - [#8555](#8555) — Qualified access and new-expressions
    - [#9459](#9459) — Resolution failure with initializer specificity
    - [#10100](#10100) — Type fields in new-expressions

- **Addressed some known bugs from 1.17**
  - An expression could not be used as a field's default value if...
    - it was a conditional-expression or loop-expression
    - the expression contained other generic fields
  - Nested types could not use initializers
  - Compilation failures for fields of certain types
    - Arrays of sync variables
    - Sparse arrays
  - And many more...
Initializers: Error Messages

● Reduced verbose output for unresolved initializer calls

```chapel
record R {
    var x: string;
    proc init(x: string) { this.x = x; }
}
var r = new R(5);
```

● In 1.17, every initializer for every type was a candidate:

```chapel
foo.chpl:4: error: unresolved call 'R.init(5)'
foo.chpl:1: note: candidates are: R.init(x: string)
$CHPL_HOME/modules/internal/ChapelLocale.chpl:101: note: locale.init()
$CHPL_HOME/modules/internal/ChapelError.chpl:55: note: Error.init()
...```

● In 1.18, only initializers on the relevant type are displayed:

```chapel
foo.chpl:4: error: unresolved call 'R.init(5)'
foo.chpl:1: note: candidates are: R.init(x: string)
```

● Otherwise improved accuracy and robustness
  ● Better line numbers; more errors issued before halting
Initializers: Enabled by Default

- Most existing modules and tests converted first
  - Increased confidence in design and implementation
  - Some constructors remain to ensure correctness while transitioning

- Deprecation warning added for user-defined constructors
  - Can be disabled with `--no-warn-constructors`

- Flipped switch so that initializers are used by default
  - Can be disabled with `--no-force-initializers`
  - Causes types without initializers to use compiler-generated initializers

```plaintext
record R {
  var x: int;
}

// In 1.17 compiler generated:
proc _construct_R(...) {
  ...}

// In 1.18 compiler generates:
proc R.init(x: int = 0) {
  this.x = x;
}
```
Initializers: Impact and Next Steps

Impact:
- Users can rely on initializers
- Warnings for constructors will prompt conversion to initializers

Next Steps:
- Add error message for user-defined constructors
  - Remove compiler code supporting constructors
- Address remaining design issues
  - Using type aliases with new-expressions
  - User-defined way to leave part of a type uninitialized ("noinit")
  - User-defined initialization for variable declarations

```c
// want to allow users to define initialization from RHS in declarations
var v: MyVector(int) = [1, 2, 3, 4];
```
Delete-Free Programming
Delete-Free Programming: Background
## Memory Management Strategies Scorecard

<table>
<thead>
<tr>
<th>Garbage Collection</th>
<th>'delete'</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ safety guarantees</td>
<td>– more errors possible</td>
</tr>
<tr>
<td>+ eliminates memory leaks</td>
<td>– failure to delete results in leaks</td>
</tr>
<tr>
<td>+ eliminates double-delete</td>
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<tr>
<td>+ eliminates use-after-free</td>
<td>– use-after-free possible</td>
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<tr>
<td>+ ease-of-use</td>
<td>– more burden on programmer</td>
</tr>
<tr>
<td>+ no need to write 'delete'</td>
<td>– think about 'delete'</td>
</tr>
<tr>
<td>– implementation challenges due to distributed memory &amp; parallelism</td>
<td>+ simpler implementation</td>
</tr>
<tr>
<td>– performance challenges</td>
<td>+ predictable, scalable performance</td>
</tr>
<tr>
<td>– stop-the-world interrupts program</td>
<td></td>
</tr>
<tr>
<td>– concurrent collectors add overhead</td>
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<td>– scalability may prove difficult</td>
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- Based on these tradeoffs, Chapel started with 'delete'
Background: Rust

- **Rust's approach prevents memory errors at compile time**
  - programs that might have a use-after-free result in compilation error
  - its *borrow checker* is the component raising these errors

- **Rust's approach also prevents race conditions**
  - since race conditions can introduce memory errors

- **Rust programmers can also write *unsafe* code**
  - provides a way to opt out of the above checking
  - expectation is that unsafe code is carefully inspected
Motivating Question

● Can Chapel include something Rust-like?
  ● compile-time detection of use-after-free?

● The Big Issue: Complete Checking and Race Conditions
  ● recall that a race condition can introduce a use-after-free error

● For example:

```plaintext
proc test() {
    var myOwned = new Owned(new MyClass());
    var b = myOwned.borrow();
    cobegin with (ref myOwned) {
        { myOwned.clear(); }  // deletes instance
        { writeln(b); }       // races to use instance before delete
    }
}
```
Complete Checking and Race Conditions

● Should Chapel rule out race conditions at compile time?

● A worthy goal, but the Rust strategy doesn't fit Chapel
  ● only one mutable reference to an object can exist at a time
  ● if a mutable reference exists, no const references to that object

● Such a strategy in Chapel would make these illegal:
  ```chapel
  forall a in A { a = 1; }
  forall i in 1..n { A[i] = i; }
  forall i in 1..n { B[permutation(i)] = A[i]; }
  ```

● Could a different strategy detect these race conditions?
  ● Maybe, but it would be difficult
  ● Can the compiler prove that 'permutation' is a permutation?
  ● If not, how would that be communicated to the compiler?
**General Goal**

- Add incomplete compile-time checking to gain some of the benefits of garbage collection

**Proposal: Lifetime Checking**

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| + low impact on execution-time program performance |
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This is the big change for existing code
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Class types were 'unmanaged' prior to this work

Class types default to 'borrowed' after this effort
class Tree {
    const left, right: Tree;
}

proc Tree.init(const depth: int) {
    if depth >= 1 {
        this.left = new Tree(depth-1);
        this.right = new Tree(depth-1);
    }
}

proc Tree.deinit() {
    delete left, right;
}

const T = new Tree(2);
dele T;
What will I have to change?

class Tree {
    const left, right: Tree;
}

proc Tree.init(const depth: int) {
    if depth >= 1 {
        this.left = new Tree(depth-1);
        this.right = new Tree(depth-1);
    }
}

proc Tree.deinit() {
    delete left, right;
}

const T = new Tree(2);
delete T;
Using unmanaged for minimal changes

class Tree {
    const left, right: unmanaged Tree;
}

proc Tree.init(const depth: int) {
    if depth >= 1 {
        this.left = new unmanaged Tree(depth-1);
        this.right = new unmanaged Tree(depth-1);
    }
}

proc Tree.deinit() {
    delete left, right;
}

const T = new unmanaged Tree(2);
delete T;
Using owned to simplify this example

```cpp
class Tree {
    const left, right: owned Tree;
}

proc Tree.init(const depth: int) {
    if depth >= 1 {
        this.left = new owned Tree(depth-1);
        this.right = new owned Tree(depth-1);
    }
}

// Tree.deinit is no longer needed since the compiler-generated one is sufficient

const T = new owned Tree(2);
// now T will be destroyed when it goes out of scope
```
Migrating Existing Programs

- The 1.18 compiler warns for code needing updates:
  - 'new C' when 'C' is a class type
    - now means 'borrowed C'; previously meant 'unmanaged C'
  - 'delete myInstance' when myInstance is a 'borrowed C'
    - 'delete' now can only be applied to 'unmanaged C'
  - these warnings will go away in future releases

- More help is available with --warn-unstable
  - warns for every undecorated class type
    - i.e., require 'owned C' / 'shared C' / 'unmanaged C' / 'borrowed C'
    - even expressions like 'new C' need to change to e.g. 'new owned C'

- Recommended code transition strategy:
  - compile with --warn-unstable
  - decorate all class types
  - optionally, replace 'borrowed C' with 'C'
Delete-Free Programming: Language Design
Class Types and New Expressions

[Note: assume 'C' is a class type in this and following slides]

- The additional keywords modify class types
  - in type declarations:
    ```
    var x: owned C
    ```
  - in 'new' expressions:
    ```
    new shared C()
    ```

- These keywords impact the class type
  - e.g. 'unmanaged C' is a different type than 'borrowed C'

- The default is 'borrowed'
  ```
  var x: C; // equivalent to 'var x: borrowed C;'
  ...new C()... // equivalent to ‘…new borrowed C()…’
  ```
Shared and Sharing

- Multiple 'shared C' variables can point to the same instance
- Assigning or copy-initializing results in sharing

```javascript
var otherShared = myShared;
// now otherShared and myShared point to the same instance
// the instance will be deleted when all references to the shared object go out of scope
```

- Default-intent 'shared' arguments also result in sharing
- 'shared' can be assigned 'nil' to release a reference

```javascript
var x = new shared C();
x = nil; // deletes the previous instance if no other shared variable refers to it
```

- Other methods are available, see 'shared' docs
Owned and Ownership Transfer

- Only one 'owned C' can point to a given instance
  - thus, it can always destroy the instance when it goes out of scope

- Assigning or copy-initializing results in ownership transfer

- ownership transfer leaves the source variable storing 'nil'
  ```javascript
  var otherOwned = anotherOwned;
  // anotherOwned now stores nil
  ```

- 'owned' can be assigned 'nil':
  ```javascript
  var x = new owned C();
  x = nil; // deletes the previous value
  ```

- Other methods are available, see 'owned' docs
Ownership Transfer on Argument Passing

- A default-intent 'owned' argument transfers ownership
- For example:

```plaintext
var global: owned C;
test();
proc test() {
    var x = new owned C();
saveit(x);  // leaves x 'nil' - instance transferred to arg & then to global
    // instance not destroyed here since x is 'nil'
}
proc saveit(arg: owned C) {
    global = arg;  // OK — Transfers ownership from 'arg' to 'global'
    // now instance will be deleted at end of program
}
writeln(global);  // OK — Prints object allocated by test() as ‘x’
```
Borrowed and Borrowing

- **What is a borrow?**
  - a pointer to a class instance that does not impact its lifetime

- **Class types default to 'borrowed’**
  - 'C' is the same as 'borrowed C'
  - 'borrowed' is appropriate for the majority of class uses

- **The 'borrow' method is available to get a borrow**

```javascript
var x = new owned C();
var b = x.borrow();
// .borrow() also available for shared, unmanaged, and borrowed objects
```
Coercions to Borrowed

- Coercions to 'borrowed' keep code simpler:

```javascript
var x = new owned C();
compute(x);  // Coerces to borrow to pass argument

proc compute(input: C) { ... }
// Could also be written as:
proc compute(input: borrowed C) { ... }
```

- Coercions available from 'owned', 'shared', and 'unmanaged'
  - User can also cast these to the corresponding ‘borrow’ type
Borrowed Arguments Don't Impact Lifetime

- An argument with borrowed type does not impact lifetime

- For example:

```plaintext
var global: borrowed C;
test();
proc test() {
  var x = new owned C();
saveit(x.borrow());
  // instance destroyed here
}
proc saveit(arg: borrowed C) {
  global = arg;  // Error! trying to store borrow from local 'x' into 'global'
delete arg;    // Error! trying to delete a borrow
}
writeln(global); // uh-oh! use-after free
```
Compile-Time Checking of Borrows

- **Lifetime checker is a new compiler component**
  - It checks that borrows do not outlive the relevant managed variable

- **For example, this will not compile:**

  ```chpl
  proc test() {
    var a: owned C = new owned C();
    // the instance referred to by a is deleted at end of scope
    var c: C = a.borrow();
    // c "borrows" the instance managed by a
    return c; // lifetime checker error! returning borrow from local variable
    // a is deleted here
  }
  
  $ chpl ex.chpl
  ex.chpl:1: In function 'test':
  ex.chpl:6: error: Scoped variable c cannot be returned
  ex.chpl:2: note: consider scope of a
  ```
Class Methods

- Class methods borrow 'this'

```plaintext
proc C.method() {
    writeln(this.type:string); // outputs the borrow type 'C'
    // a.k.a. 'borrowed C'
}
```

- Coercions to borrow enable method calls on 'owned'

```plaintext
var x = new owned C();
x.method(); // 'this' argument coerces to borrow in call
```
Class Subtyping

- **All class value kinds support subtyping**
  - Example shows 'owned', but 'shared', 'unmanaged', 'borrowed' all work

```plaintext
class ParentClass { ... }
class ChildClass: ParentClass { ... }

proc consumeParent(arg: owned ParentClass) { ... }
var x = new owned ChildClass();
consumeParent(x); // coerces 'owned ChildClass' to 'owned ParentClass'
                  // and consumes x, leaving it 'nil'

proc borrowParent(arg: ParentClass) { ... }
var y = new owned ChildClass();
borrowParent(y); // coerces 'owned ChildClass' to 'borrowed ParentClass'
                  // y still stores an object after this call
```
'new C' and 'new borrowed C'

● What happens with an undecorated 'new'?

```javascript
var a = new C();
```

● Here the type of 'a' is a 'borrowed C'
  ● the instance will be destroyed at the end the current block
  ● ownership transfer or sharing are not possible
  ● returning 'a' results in a compilation error

● The following are also equivalent to the above:

```javascript
var a: C = new owned C();  // coercing to borrow
var a = (new owned C()): C;  // casting to borrow
var a = (new owned C()).borrow();
```
'new C': Why Create a Borrow?

● Keeps type inference consistent:

```plaintext
var a = new C();
// equivalent to
var a: C = new C();
```

● Memory is managed automatically
   ● instance automatically deleted at the end of the enclosing block
   ● similar to records (and other Chapel types)

● Avoids accidental ownership transfer
   ● any attempts to transfer ownership will result in compilation error

● Values created have same performance as 'unmanaged'
   ● 'owned' and 'shared' have different representations
**Task Intents for 'owned' and 'shared'**

- **for all loops and tasks default to borrowing outer variables**
  ```
  var outerOwnedC = new owned C();
  
  coforall i in 1..n {
    ...
    outerOwnedC ...
    // in the loop, outerOwnedC has type 'borrowed C'
  }
  
  forall i in 1..n {
    ...
    outerOwnedC ...
    // in the loop, outerOwnedC has type 'borrowed C'
  }
  ```
  - avoids race conditions of a 'ref' or 'in' default
  - avoids extra indirection of a 'const ref' default
  - as always, users can override this default using task intents
Generic Arguments Default to Borrowed

- Totally generic arguments don't transfer ownership
  - e.g. 'proc f(arg)' or 'proc f(arg: ?t)'

```plaintext
proc f(x) { ... }
var x = new owned C();
f(x);
writeln(x); // does not output `nil` since `f` borrowed
```

- Instead, such generic arguments need to opt in:

```plaintext
proc f(x) { ... }
f(new owned C()); // f gets a borrow

proc g(x: owned) { ... }
g(new owned C()); // g takes ownership
```

- Need more experience with this rule
Generic Arguments Default to Borrowed: Advantages

● Ownership transfer for such functions can be surprising
  ● variables might suddenly become 'nil'

```plaintext
proc f(x) { ... }
var x = new owned C();
f(x);
writeln(x); // would be 'nil' without the rule
```

● Function signatures show potential for ownership transfer
  ● so library users can understand APIs
  ● 'proc f(x)' does not indicate ownership transfer
  ● 'proc f(x: owned)' does

● Consistent with task/forall intent case
Generic Arguments Default to Borrowed: Disadvantages

● Change of type in instantiation can be surprising
  ● unlike behavior of other types, so could be hard to explain
    
    ```
    proc printTypeOfArg(arg) {
      writeln(arg.type: string);
    }
    
    var x = new owned C();
    printTypeOfArg(x); // is it surprising that it outputs 'borrowed C'?  
    ```

● Compile-time checking for 'nil owned' might be better
Delete-Free Programming: Status in 1.18
Status in 1.18: Class Kinds

- Implemented new class kinds as described
- Implemented --warn-unstable to help with code transition
- Implemented functionality described in preceding slides
Status in 1.18: Lifetime Checking

- Lifetime checker can detect many errors at compile-time
  - returning a borrow from a local variable
  - returning a reference to a local variable
  - assigning a borrow from a local to a global
  - ...

- Certain cases still need improvement / have bugs
  - loop-expressions
    ```
    var x = [i in 1..3] new borrowed C(i);
    ```
  - initializers
    ```
    proc init() { this.x = new borrowed C(); }
    ```
  - checking not yet supported for top-level statements in modules
Delete-Free Programming: Next Steps
Next Steps: Lifetime Checking

- **Need syntax for expressing lifetimes**
  - return lifetimes
  - constraints among arguments

- **Need to check constraints among arguments at calls**
  - need to be able to express constraints among arguments
  - need to check such constraints
    - 'array.push_back()' is a good example
    - elements added need to have lifetime >= array lifetime

- **Need some checking of invalidations**
  - e.g., recognize that 'owned.clear()' makes borrows invalid
  - domain resizing is another example

- **Need some checking of 'nil' dereferences**
  - at least when compiler can prove 'nil' will be dereferenced
Next Steps: Class Types

- Is the design for totally generic arguments correct?
- Should language express nil-ability of class types?
  - so compiler could do more complete checking 'nil' dereferences
- Should methods be able to request 'unmanaged this'?
Shape Preservation for Loop Expressions and Promotions
Shape Preservation: Background

- For-, forall-, and promoted expressions can create arrays:

```plaintext
var InputData: [D] real = ....; // create some array
var Aser = for d in InputData do computeValue(d);
var Apar = [d in InputData] computeValue(d);
var Apromo1 = computeValue(InputData); // promoted computeValue()
var Apromo2 = Aser + Apar; // promoted ‘+’
```

- In the past, each A* array above had the domain: {1..D.size}
  - 1-dimensional, 1-based indexing regardless of the domain ‘D’
  - This has never been the intended behavior, yet it’d never been fixed
  - Libraries like LinearAlgebra have been impacted:
    - instead of:
      ```plaintext
      var C = A + B; // C would lose the shape of A
      ```
    - needed to write:
      ```plaintext
      var C = A.plus(B); // C has the shape of A; but the notation is less elegant
      ```
Shape Preservation: This Effort

- As of Chapel 1.18, A* arrays below have the domain ‘D’
  - D can be multi-dimensional, distributed, associative, ...

```chapel
var InputData: [D] real = ....; // create some array
var Aser = for d in InputData do computeValue(d);
var Apar = [d in InputData] computeValue(d);
var Apromo1 = computeValue(InputData); // promoted computeValue()
var Apromo2 = Aser + Apar; // promoted ‘+’
```
Shape Preservation: Impact

● More intuitive “shapeful” outcome
  ● ex. with array operations

```plaintext
var A, B: [1..n, 1..m] real;
var C = A + B;
```

**C used to be “shape-less”**
1-d, computed serially

**It is now 2-d, computed in parallel**

● Parallel initialization of arrays
  ● from forall- and promoted expressions

● Note: no shape preservation for filtering predicates:

```plaintext
// if A.domain were InputData.domain, some of A's elements could be left uninitialized
var A = for d in InputData do if d > 0 then computeValue(d);
```
Shape Preservation: Status

● **Available in 1.18, except:**
  ● no shape preservation, no parallelism when the iterable is a range
    ```
    var A = [i in -n..n] computeValue(i);  // A.domain is {1..2*n+1}
    ```
  
  ● cannot build arrays of arrays
    ```
    var A = [i in {-n..n}] makeArray(i);  // run-time error
    ```

● **Working on supporting these cases for upcoming releases**
Shape Preservation: Next Steps

- **Implement missing functionality:**
  - shape preservation with ranges
    - ensure parallel execution
  - arrays of arrays built using loop expressions and promotions
    - this will expand availability of “skyline” (or “jagged”) arrays
Shape Preservation: Next Steps in Design

● **Design choices:**
  ● how should a formal behave when called with a shapeful actual?
    ```
    myFun( [i in D] f(i) );
    proc myFun(arg) {
        // Is 'arg' an array or an iterator expression? Can we query its shape?
    }
    ```
  
  ● allow iterators to declare their resulting shape
    ```
    iter shapeful() {
        forall idx in MyDomain do yield idx;
    }
    var MyArr = shapeful();
    // want MyArr.domain to be MyDomain
    ```
Task-Private Variables
Task-Private Vars: Background

- **Task-private variables are helpful in data-parallel codes**
  - Create a separate variable for each task during execution
  - No need to synchronize the accesses
  - Each variable is allocated “close” to the executing core

```haskell
forall elem in MyData {  
  var s: Scratch;  
  … process each ‘elem’ using scratch space in ’s’ …  
}

forall elem in MyData with (var s: Scratch) {  
  … process each ‘elem’ using scratch space in ’s’ …  
}
```

‘s’ is task-private, allocated just once per task

‘s’ is allocated / deallocated for each iteration
Task-Private Vars: This Effort and Impact

- Task-private variables are now available in forall-loops
- Can be var, const, ref, or const ref

```plaintext
forall elem in MyData with {
  // Declare a task-private variable via its type…
  var scratchInt: int,
  // …and/or its initial value:
  var scratchRecord = new Scratch(),
  // Task-local copies may provide faster access:
  const localCopy = globalArray,
  // Task-local copies can focus on local data:
  ref localSlice = distArray[myLocInds()]
}

... process ‘elem’ ...
```
Task-Private Vars: Next Steps

- Gain more experience with task-private variables
- Consider providing “locale-private” variables
  - create a variable / compute its initializer just once per locale
  - share it between all tasks spawned on that locale
- Consider providing task startup and tear-down blocks
  - execute given code at start / end of each task within a forall loop
  - also, per-locale startup / tear-down blocks?
- Handle errors thrown during task-private var initialization
Override Checking
Override: Background

**Overriding supports method dispatch at execution time:**

```python
class Parent {
    proc method() { }
}

class Child: Parent {
    proc method() { }
}

var x: Parent = new Child();
x.method();  // virtual dispatch based on runtime type—calls Child.method()
```
Override: Errors

- **Many ways to unintentionally mess it up:**
  - Misspelled function name?
  - Different argument names?
  - Different argument types?
  - Different argument intents?

- **Additionally, library changes can have surprising impact:**
  - subclass thinks it’s creating a new method, but overrides a parent’s
    - or vice-versa
  - see [CHIP 20 section "Overriding"]
Override: Errors

Does it override?

<table>
<thead>
<tr>
<th>proc Parent.a(arg: real)</th>
<th>proc Child.a(arg: real)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proc Parent.b(arg = 1)</td>
<td>proc Child.b(arg: int)</td>
</tr>
<tr>
<td>proc Parent.c(arg: uint)</td>
<td>proc Child.c(arg: int)</td>
</tr>
<tr>
<td>proc Parent.d(arg)</td>
<td>proc Child.d(arg: int)</td>
</tr>
<tr>
<td></td>
<td>?</td>
</tr>
<tr>
<td>proc Parent.e(arg: int)</td>
<td>proc Child.e(arg)</td>
</tr>
<tr>
<td></td>
<td>?</td>
</tr>
<tr>
<td>proc Parent.f(arg)</td>
<td>proc Child.f(x)</td>
</tr>
</tbody>
</table>

? = it depends on the arguments for instantiations
Override: This Effort

● **Added ‘override’ keyword and now require its use**
  ● Methods that override a parent class method must be marked
    ```ruby
    proc Parent.method() { }
    proc Child.method() { }  // warning: overrides but missing keyword
    
    proc Parent.method() { }
    override proc Child.method() { }  // OK
    
    proc Parent.method() { }
    override proc Child.methodid() { }  // error: no superclass method matches
    ```

● **Compiler raises an error if a marked method does not override**
  ```ruby
  proc Parent.method() { }
  override proc Child.method() { }  // error: conflicting intent
  ```

● **Check that intents match for cases we previously missed**
  ```ruby
  proc Parent.method(in arg: string) { }
  override proc Child.method(arg: string) { }  // error: conflicting intent
  ```
Override: Impact, Next Steps

**Impact:** Overriding is less error-prone

**Next Steps:** Make missing ‘override’ an error, not a warning
Namespace / Resolution Improvements
Namespace Improvements: Background

- **Namespaces are a code organization strategy**
  - Modules, functions, classes/records all create namespaces
  - Symbols defined within a module can be accessed from outside it via…
    - the module prefix: `M.foo()`
    - a `use` statement, enabling access without the prefix:
      ```
      use M;
      foo(); // defined in module M
      ```

- **When symbols share a name, rules define which to access**
  ```
  module Outer {
    var x = 10;
    module Inner {
      var x = 3;
      writeln(x); // prints 3 since Inner.x is more relevant than Outer.x
    }
  }
  ```
Namespace Improvements: Background

● Sometimes these access rules are surprising
  ● For instance, function disambiguation is tricky
    ● See CHIP 20 on Function Hijacking
  ● Not always clear when functions/methods were visible
    ● Visibility rules needed to be revisited
    ● Some unintentional behavior

● This release, looked at three specific cases:
  ● Function disambiguation when considering the point of instantiation
  ● Field access and method calls when type is obtained outside its scope
  ● Bug when private and public functions in same scope share a name
Function Preference: Background

- Consider this example program
- Which 'setup()' method should be called from ‘run()'?

```haskell
module Library1 {  
  proc setup() {...} // #1

  proc run(x) {  
    setup(); // setup() #1 or #2 ?
  }
}

module Application1 {  
  use Library1;
  proc setup() {...} // #2
  proc main() {  
    run(1);
  }
}
```
Which visibility scope is preferred?
- Prefer point of definition → choose setup() #1
- Prefer point of instantiation → choose setup() #2

Traditionally, our compiler has done this

```plaintext
module Library1 {
  proc setup() {...} // #1
  proc run(x) {
    setup(); // setup() #1 or #2 ?
  }
}

module Application1 {
  use Library1;
  proc setup() {...} // #2
  proc main() {
    run(1);
  }
}
```

Function Preference: Background

```plaintext
proc run(x: int) point of instantiation
proc run(x) point of definition
```
Function Preference: This Effort

- Now prefer functions from point of definition (#1)
  - Result is less surprising to library authors
  - See CHIP 20 for rationale

```plaintext
module Library1 {
    proc setup() {...} // #1
    proc run(x) {
        setup(); // setup() #1 or #2 ?
    }
}

module Application1 {
    use Library1;
    proc setup() {...} // #2
    proc main() {
        run(1);
    }
}
```
Module Visibility: Background

- If not named in a ‘use’ clause, members were not visible

```plaintext
module M {
    record Foo {
        ...
        proc method1() {...}
    }
}
```

```plaintext
use M only; // method1() not named here...
var x = new M.Foo();
x.method1(); // …so it wasn’t visible here
```

- Private overloads sometimes shadowed public routines

```plaintext
module M {
    proc foo() { ... }
    private proc foo() { ... }
}
```

```plaintext
M.foo(); // private foo() shadowed public
```
Module Visibility: This Effort

- Filtered module uses no longer prevent member accesses

```javascript
module M {
  record Foo {
    ...
    proc method1() {...}
  }
}

use M only;

var x = new M.Foo();
x.method1(); // now works!
```

- However, such cases don’t work yet without a ‘use’ statement

- Private routines no longer shadow public ones

```javascript
module M {
  proc foo() { ... }
  private proc foo() { ... }
}

M.foo(); // now works!
```
Namespace Improvements: Next Steps

- Public/private fields and methods
  - Possibly also something like “protected”?

- Public/private ‘use’ statements to control transitivity

- Perennial request to support “‘use’ nothing by default”

- Should modules be able to be extended from without?
  - Similar to C++, D
  - If so, what syntax should be used?
    - Example proposals at issues [10909](#) and [10946](#)
Namespace Improvements: Next Steps

- Consider implementing overload sets

- Investigate alternatives to the point-of-instantiation rule
  - 'implements' statements in constrained generics / interfaces
  - Interaction with intended first-class-function / function object support

- Relationship between ‘mason’ packages and namespaces
Enumerated Type Improvements
Enum Fixes: Background and This Effort

Background:

- Due to int coercions, Chapel enums have been fairly impure (C-like)
  - Given:
    
    ```
    enum color {red, green, blue};
    enum size {small=0, medium=1, large=2};
    ```

  - Users could write:
    
    ```
    ...color.red + size.medium... // does it make sense to add colors and sizes?
    ...color.red: int... // do enums count from 0 or 1 implicitly?
    ```

  - Enum ranges haven’t been supported, so such cases coerced to int ranges:
    
    ```
    for s in color.red..color.blue do ... // ‘s’ is an ‘int’, not a ‘color’
    var A: [size.small..size.large] real; // effectively ‘A: [0..2] real’;
    ```

This Effort:

- Made enums more pure and strict; less error-prone
- Addressed some related omissions and inconsistencies
Enum Fixes: No more coercions to int

This Effort: Stopped supporting enum-to-int coercions

Impact:

- Reduces opportunities for writing surprising code patterns:
  - ...color.red + size.medium... // error: no longer legal
  - 1..10 by color.blue // error: no longer legal
- Requires using casts to convert enums to integers:
  - if size.large:int & 0x1 // use casts to compute using integer values
- ...or custom overloads can be written:
  - proc +(c: color, s: size) { ... }
- Avoids longstanding questions about “What kind of int is this enum?”
  - signed or unsigned?
  - how many bits?
  - what if I want to change the default?
Enum Fixes: No implicit integer values

This Effort: Enums have integer values only when specified

● Given:
  ```
  enum color {red, green, blue}; // colors don’t have int values
  enum size {small=0, medium=1, large=2}; // sizes do
  ```

● User can write:
  ```
  ...size.large:int... ...mySize:int...
  ```

● But not:
  ```
  ...color.red:int... ...myColor:int...
  ```

Impact:

● Supports pure enums that don’t have associated integer values
● Avoids confusion about whether enum values start at 0 or 1
  ● user specifies values only if/when they want them
  ● note that enum numbering continues once started, so size could be written:
    ```
    enum size {small=0, medium, large};
    ```
Enum Fixes: Support for enum ranges

This Effort: Ranges of enums are now supported
- Also rectangular domains and arrays over enums

Impact:
- Given:
  ```
  enum color {red, orange, yellow, green, blue, indigo, violet, white, brown, black};
  ```
- Can now write:
  ```
  const spectrum = color.red..color.violet;
  const colorDom = {color.red..color.black};
  var colorGrid: [spectrum, color.red..color.black] bool;
  ```
- Supports natural uses of enums for loops and data structures
- Results in better efficiency than associative domains/arrays of enums
  ```
  var assocColorDom: domain(color); // O(n) hash table implementation
  var rectColorDom: domain(rank=1, color); // O(1) low/high bounds
  ```
Enum Fixes: Relational operators on enums

This Effort: Relational operators supported for each enum type

- **Definition:**
  - compares the *order* of the enum symbols, not their integer values

- **Rationale:**
  - all enums are ordered, but not all have integer values (as of this release)
  - interpretation corresponds to how enums are treated within ranges
  - users who want to compare int values can cast or overload ops themselves

Impact:

- **Given:**
  ```
  enum color {red=0xff0000, green=0x00ff00, blue=0x0000ff};
  enum size  {small=0, medium=1, large=2};
  ```

- **Behavior:**

<table>
<thead>
<tr>
<th>Expression</th>
<th>Was</th>
<th>Now</th>
</tr>
</thead>
<tbody>
<tr>
<td>color.red &lt; size.small</td>
<td>false</td>
<td></td>
</tr>
<tr>
<td>color.red &lt; color.blue</td>
<td>false</td>
<td>true</td>
</tr>
<tr>
<td>size.small &lt; size.large</td>
<td>true</td>
<td>true</td>
</tr>
</tbody>
</table>

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Enum Fixes: Associative domains of enums

**Background:** Associative enum domains have been inconsistent

- Associative domains are typically empty by default:
  ```
  var intSet: domain(int);       // empty set of integers
  var strSet: domain(string);    // empty set of strings
  ```
- However, associative domains of enums have been full by default
  ```
  var colorSet: domain(color);   // full set of enums: {red, green, blue}
  ```
- Historical rationale:
  - “arrays mapping from all enum members to values are a common case”
  - couldn’t use rectangular domains over enums since they weren’t supported
  - “enums tend to be small / finite sets (in contrast to integers, strings, etc.)”
  - “users can always clear the domain if they don’t want it to be full”

**This Effort:**

- Treat associative domains of enums like other cases
- Old rationale falls apart given support for rectangular enum domains
  - now have a concise and efficient way to map from enums to values
  - permits us to opt for consistency over convenience
Enum Fixes: Status & Next Steps

Status:
- Enums are much more principled today as a result of these changes
  - Yet, they can also still be used as integers when desired
- This work also led to support for ranges of bools being added
  - (as well as rectangular domains and arrays over bools)

Next Steps:
- Further design decisions (GitHub issue #10434):
  - representation of enums in binary files?
  - implications of duplicate integer values in enums?
  - how to specify different bit widths when storing enums?
  - permit enums to be associated with non-param integer values?
  - enum +/- integer operator overloads with ordinal interpretations?
- Opportunities for optimizing implementation of enum operations
- Support for ranges of other types? (bigint! real? user-defined types?)
Type Constraint Improvements
Constraints: Background

- Migrating tests to 'owned' etc. revealed problems
- Problems had to do with type constraints
  - especially for generic types
  - 'owned', 'borrowed', etc. are now generic types
- Several patterns needed improvement:
  - Colon in where-clauses
  - isSubtype()
  - Type comparison operators
  - Variables and fields with generic declared types
  - Generic argument types
Constraints: Colon in Where-Clauses

Background: Colons in where-clauses constrained types
- Despite being a cast, syntactically
- This special case was undocumented

```plaintext
record R { var x; }
proc f(arg) where arg.type: R { }
// this 'f' can only be called when 'arg' is a subtype of R, including instantiations
```

This Effort: Deprecated special handling for ‘:’ in where-clauses
- Use of colon in where-clauses now emits a warning
  - but continues to behave as before, for now
- Code should switch to using isSubtype() instead
  - note that isSubtype() now considers numeric coercions
  - previous support for ‘:’ in where-clauses did not

Impact: Removed undocumented special case
Constraints: isSubtype()

Background: isSubtype() was incomplete
- Could not check for instantiations of a generic type:
  ```plaintext
code snippet
record R { var x; }
isSubtype( R(int), R )  // failed to compile
isSubtype( int, integral )  // failed to compile
```
- Did not include compiler-supported coercions
  ```plaintext
code snippet
isSubtype( int(8), int(64) )  // was false
```

This Effort: Addressed above problems
- Above cases now all compile and result in 'true'

Impact: isSubtype() and isProperSubtype() now more capable
- enabling them to replace uses of ‘.’ in where-clauses
Constraints: Type Comparison Operators

**Background:** Language supported only ‘==’ and ‘!=' on types

```plaintext
int == int // 'true'
real == int // 'false'
real != int // 'true'
int(8) < int(64) // failed to compile
```

**This Effort:** Enabled comparison operators on types

- ‘<’, ‘>’, ‘<=’, ‘>=’ are now available on types
- form alternative ways to write isProperSubtype() and isSubtype()
- ‘A < B’ translates to ‘isProperSubtype(A, B)’
  - similar to the normal ‘A <: B’ notation in programming language theory
  - ‘int(8) < int(64)’ results in 'true' as one intuitively expects

**Impact:** Type comparison works with all comparison operators

**Next steps:** Allow == and != with generic types
Constraints: Generic Declared Types

**Background:** Variable declarations can optionally specify type:

- // the type of x is inferred:
  ```
  var x = someExpression();
  ```
- // ensure the type of someExpression() is, or is convertible to, SomeType:
  ```
  var x: SomeType = someExpression();
  ```
- // generic constraints were not supported:
  ```
  record R { var impl; }
  var y: R(int) = someExpression();  // OK
  var z: R = someExpression();       // did not compile
  ```

**This Effort:** Variables and fields can have generic declared types

- ```
  var z: R = someExpression();  // now works
  ```

  - asserts that someExpression() is convertible to an instantiation of R
  - generic declared type can also be used in field declarations

**Impact:** Enabled more patterns to work with 'owned' and 'shared'
Constraints: Generic Argument Types

**Background:** Argument types support generic instantiations

```java
class C { var x; }
record R { var impl; }
proc f(arg: R) { } // 'arg' accepts any instantiation of 'R'
proc g(arg: R(C(int))) { } // 'arg.impl' must be of type C(int)
proc h(arg: R(C)) { } // arg.impl should be an instantiation of C
    // this case failed to compile
```

**This Effort:** Fix type arguments with nested generic types

- ‘h()' case above now works

**Impact:** Enabled more code to migrate to 'owned' and 'shared'

**Next steps:** Fix related bugs in the implementation

```java
proc tupleIssue(arg: 2*?t)
proc integralIssue(arg: R(integral))
```
Sidebar: Reduced Compilation Time
Compilation Time: Background

- Chapel compilation time needs improvement
  - we know the Chapel compiler is too slow
  - improving it will require significant effort

- Function resolution frequently takes the most time

- Compilation time has been increasing
  - as compiler features are added
  - as default module code is added
Compilation Time: This Effort, Impact

This Effort: Simplified module code by removing where-clauses
- part of the effort to deprecate ':' in where-clauses
- many of the where-clauses were not necessary
  - declared types on arguments could suffice
  - especially for type arguments used for defining cast functions

Impact: Improved resolution time
- especially by reducing work required to resolve casts
UTF-8 String Support
UTF-8 Support: Background

- Chapel has gradually been gaining Unicode support
  - in particular for UTF-8 in strings

- Chapel supported UTF-8 in some ways but not others
  - Chapel string literals could be defined as UTF-8 strings
  - the I/O system could work with UTF-8
  - some string methods were confused by UTF-8
  - testing of UTF-8 was very light
UTF-8 Support: Background

- **Unicode is a widely used character encoding**
  - 21-bits per code point
  - intended to represent all languages

- **Characters in Unicode are called *code points***

- **UTF-8 is an encoding of *code points* into bytes**
  - each code point is represented by a number of bytes (1 to 4)
  - ASCII strings are already valid UTF-8 strings

- **Unicode includes *combining characters***
  - e.g., the accent ´ can be represented separately
  - combines with the character before it to form ‘é’, for example

- **The combined symbol displayed is called a *grapheme***
  - uses multiple code points when combining characters are present
UTF-8 Support: Background: UTF-8

- For example:

<table>
<thead>
<tr>
<th>string</th>
<th>code points</th>
<th>UTF-8 bytes (hexadecimal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>U+0065</td>
<td>65</td>
</tr>
<tr>
<td>é</td>
<td>U+00E9</td>
<td>C3 A9</td>
</tr>
<tr>
<td>é</td>
<td>U+0065 U+0301</td>
<td>65 CC 81</td>
</tr>
</tbody>
</table>

1 grapheme
2 code points
3 UTF-8 bytes
UTF-8 Support: This Effort

- Updated existing string methods to support UTF-8
- isAlpha() and related routines only worked with ASCII
  - users need to be able to check for particular UTF-8 strings
  - implementation was confused by UTF-8 strings and returned 'false'
- Now, they support UTF-8 strings

```javascript
var s: string = "événement";
if s.isLower() { // now returns true instead of false
    ...
}
```
UTF-8 Support: This Effort

- Added new string methods for UTF-8 support
  - 'string.ulength'
    - returns the number of code points
  - 'string[codePointIndex]'
    - accesses the character at a given code point offset
      - slow because it must traverse the string to find where each character starts
  - 'string.uchars()' iterates over the code points
    - returns integers, yet 'string.these()' returns strings

```javascript
var s: string = "événement";
for ch in s.uchars() {
    // manipulate 21-bit Unicode character
}
```
UTF-8 Support: This Effort

- What should these routines do for this example?

<table>
<thead>
<tr>
<th>string</th>
<th>code points</th>
<th>UTF-8 bytes (hexadecimal)</th>
<th>.length</th>
<th>[1] (indexing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>U+0065</td>
<td>65</td>
<td>1</td>
<td>&quot;e&quot;? 0x65?</td>
</tr>
<tr>
<td>é</td>
<td>U+00E9</td>
<td>C3 A9</td>
<td>2? 1?</td>
<td>&quot; é&quot;? 0xE9? &quot;é&quot;?</td>
</tr>
<tr>
<td>é</td>
<td>U+0065 U+0301</td>
<td>65 CC 81</td>
<td>3? 2? 1?</td>
<td>&quot;é&quot;? 0x65? &quot;é&quot;?</td>
</tr>
</tbody>
</table>
UTF-8 Support: This Effort

● Identified high-level design questions
  ● Is only one multibyte string representation supported, or many?
    ● if many, is it set per program or per string?
  ● Can a string store non-UTF-8 data, e.g. binary data?
  ● Can one explicitly request byte or code-point indexing?
  ● Is indexing and slicing by integers supported?
    ● if so, what is the unit for the offsets? grapheme, code point, or byte?
  ● Will the library support C-like character classes?
  ● Will the library support Unicode Character Properties?
  ● Will the library support indexing and iteration by grapheme?

● Identified API design questions
  ● Do indexing and iteration return a 'string' or a numeric type?
UTF-8 Support: This Effort

- Identified high-level design questions
  - Is only one multibyte string representation supported, or many? currently many
    - if many, is it set per program or per string? program
  - Can a string store non-UTF-8 data, e.g. binary data? yes
  - Can one explicitly request byte or code-point indexing? yes
  - Is indexing and slicing by integers supported? yes
    - if so, what is the unit for the offsets? grapheme, code point, or byte? byte
  - Will the library support C-like character classes? yes
  - Will the library support Unicode Character Properties? no
  - Will the library support indexing and iteration by grapheme? no

- Identified API design questions
  - Do indexing and iteration return a 'string' or a numeric type? varies
UTF-8 Support: Status & Next Steps

Status:
- Expanded 'string' support for UTF-8
  - more string methods are UTF-8 aware
- Implemented prototypical Unicode-specific methods
- String API is not yet stable

Next Steps:
- Reach consensus on the design questions
- Implement slicing with code point offsets
- Stabilize the string API
Param Renaming of Extern/Export Procedures
Param Renaming of Export/Extern

Background:
- Chapel has supported renaming of exported/extern routines via strings
  ```
  extern "atoi" proc c_atoi(arg: c_string): c_int;
  // Chapel code can now call 'c_atoi'
  // such calls invoke the C function 'atoi'
  ```

This Effort:
- Extended support to include arbitrary param string expressions
  ```
  extern getAtoi() proc c_atoi(arg: c_string): c_int;
  config param prefix = "";
  proc getAtoi() param { return prefix + "atoi"; } 
  ```

Impact:
- Enabled significant simplification of the Atomics module (next slide)
- now 2000 lines shorter and easier to maintain
- simplified implementation of buffered atomics
Param Renaming of Export/Extern: Atomics

- Atomics module had methods for each int/uint/real size
  
  ```
  proc fetchAdd(value:int(64)): int(64) {
    extern proc atomic_fetch_add_int_least64_t(ref obj:atomic_int_least64_t, operand:int(64)):int(64);
    var ret: int(64);
    on this do ret = atomic_fetch_add_int_least64_t(_v, value);
    return ret;
  }
  // repeated 9 times for other int, uint, and real sizes
  ```

- Now a single generic method
  
  ```
  proc fetchAdd(value: T): T {
    extern "atomic_fetch_add_" + externTString(T)
    proc atomic_fetch_add(ref obj:externT(T), operand:T): T;
    var ret: T;
    on this do ret = atomic_fetch_add(_v, value);
    return ret;
  }
  ```
Generic Array Return Types
Array Return Types: Background

● Could only declare fully explicit or inferred array returns

```plaintext
proc foo(): [1..3] int { ... }
proc foo() {  // Supported; Return type inferred from return statements
    var A: [1..3] int;
    return A;
}
```

● Leaving off just the domain or element type not supported

```plaintext
proc foo(): [] int { ... }  // Not allowed, needed domain
proc foo(): [1..3] { ... }  // Not allowed, needed element type
proc foo(): [] { ... }      // Not allowed, needed domain and element type
```

● Array arguments supported any combination of these
Array Return Types: This Effort & Next Steps

This Effort:
● Added support for declaring partially inferred array return types
  
  \[
  \begin{align*}
  \text{proc } &\text{ foo}() : [] \text{ int } \{ \ldots \} \quad // \text{ Works} \\
  \text{proc } &\text{ bar}() : [1..3] \{ \ldots \} \quad // \text{ Works} \\
  \text{proc } &\text{ baz}() : [] \{ \ldots \} \quad // \text{ Works}
  \end{align*}
  \]

Next Steps:
● Add similar support for iterators
Improvements to Method Forwarding
Forwarding: Background, This Effort

**Background:** Chapel supports method forwarding

```chapel
record R {
  forwarding var instance;
}
var myRecord = new R(new MyClass);
myRecord.myMethod(); // calls MyClass.myMethod() if available
```

**This Effort:** Fixed bugs by changing implementation strategy

- compiler now attempts to handle forwarding by adjusting callsite
- the previous strategy involved creating a wrapper function
Forwarding: Impact, Status

**Impact:** Resolved eight forwarding issues
- forwarding now supports coercions
  - supports forwarding to an 'owned' instance
- forwarding now works with return intent overloading
- forwarding now supports accessing type and param fields

**Status:** Forwarding is now used regularly in internal library
'in' Intent Improvements
'in' intents: Background

**Background:** Since 1.17, 'in' intents act like variable initialization

- For example, the following:
  ```
  foo(<expr>);
  proc foo(in arg) { ... }
  ```
- ...is similar to:
  ```
  foo();
  proc foo() {
    var arg = <expr>;
  }
  ```

- However, the implementation had some problems with corner cases
  - 'in' intent arguments with default value expressions
  - unnecessary copies for certain actual args (e.g., 'new MyRecord()')
  - 'in' intent formals with runtime types (e.g., domains and arrays)

**This Effort:** Fixed corner cases
'in' intents: Status, Next Steps

Status: No known problems with 'in' intent

Next Steps: Solidify related language design choices
- Avoid unnecessary copies when possible
- Consider improving:
  - 'out', 'inout' intents
  - copies from expiring values in general
Dynamic Dispatch with Variable Arguments
**Background:** Dynamic dispatch failed for vararg methods

- The method corresponding to the static class type was called instead

```java
class P { ... }
class C: P { ... }

proc P.extend(a: int...) {
    return ("Parent", (...a));
}

override proc C.extend(a: int...) {
    return ("Child", (...a));
}

var pc: P = new C();
writeln(pc.extend(1,2,3)); // Printed (Parent, 1, 2, 3)
```
Dynamic Dispatch with Varargs: This Effort

This Effort: Enable dynamic dispatch for varargs methods

- The varargs call is now dynamically dispatched to the Child method

```plaintext
class P { ... }
class C: P { ... }

proc P.extend(a: int...) {
    return ("Parent", (...a));
}

override proc C.extend(a: int...) {
    return ("Child", (...a));
}

var pc: P = new C();
writeln(pc.extend(1,2,3));  // Prints (Child, 1, 2, 3)
```
Improvements to Arrays, Domains, and Domain Maps
Array-as-Vector Improvements
Array-as-Vector Improvements

**Background:** 1-D arrays provide several vector operations

```plaintext
A.push_back(x);
A.pop_front();
```

etc.

- Getting the first or last array element required finding the index
  ```plaintext
  var front = A[A.domain.low],
  back = A[A.domain.high];
  ```

- The pop methods removed the first or last element, but didn't return it

**This Effort:** Simplify getting a copy of the first or last value

```plaintext
var front = A[A.domain.low];
var oldBack = A[A.domain.high];
A.pop_back();
```

```plaintext
var front = A.front();
var oldBack = A.pop_back();
```

**Impact:** Simplified codes using array vector operations
Sorting Sparse Indices for LayoutCS
Sorting Sparse Indices for LayoutCS

Background:
- Our CSR/CSC sparse domains have typically stored indices sorted
  - helps random access/insert, but can add overhead in some cases
  - sparse matrix-matrix multiplication was one case that was hurt by sorting

This Effort:
- Added options to support storing CSR/CSC indices unsorted
  - config param `LayoutCSDefaultToSorted` sets global default
  - per-domain map argument `sortIndices` can override for a given case

Impact:
- Sorting can help or hurt computations depending on operation mix
  - see section on LinearAlgebra improvements for an example

Next steps:
- Continue to optimize and tune sparse array operations
For More Information

For a more complete list of language changes in the 1.18 release, refer to the ‘Semantic Changes’, ‘Feature Improvements’, ‘Standard Domain Maps’ and ‘Bug Fixes’ sections in the CHANGES.md file
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