Module 3: MultiDimensional Loops and Data Structures

April 25, 2024
Module 1: Introduction, Building and Parallel Dispatch
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Reserve Day
Kokkos EcoSystem
Data Parallelism:

- Simple parallel loops use the `parallel_for` pattern:
  ```
  parallel_for("Label", N, [=] (int64_t i) {
  /* loop body */
  });
  ```

- Reductions combine contributions from loop iterations
  ```
  int result;
  parallel_reduce("Label", N, [=] (int64_t i, int& lres) {
  /* loop body */
  lres += /* something */
  },result);
  ```
Kokkos View

▶ Multi Dimensional Array.
▶ Compile and Runtime Dimensions.
▶ Reference counted like a std::shared_ptr to an array.

Kokkos::View<int*[5]> a("A", N);
a(3,2) = 7;

Execution Spaces

▶ Parallel operations execute in a specified Execution Space
▶ Can be controlled via template argument to Execution Policy
▶ If no Execution Space is provided use DefaultExecutionSpace

// Equivalent:
parallel_for("L", N, functor);
parallel_for("L",
    RangePolicy<DefaultExecutionSpace>(0, N), functor);
**Memory Spaces**

- Kokkos Views store data in **Memory Spaces**.
- Provided as template parameter.
- If no Memory Space is given, use `Kokkos::DefaultExecutionSpace::memory_space`.
- `deep_copy` is used to transfer data: no hidden memory copies by Kokkos.

```cpp
View<int*, CudaSpace> a("A", M);
// View in host memory to load from file
auto h_a = create_mirror_view(a);
load_from_file(h_a);
// Copy
deep_copy(a,h_a);
```
Layouts

- Kokkos Views use an index mapping to memory determined by a Layout.
- Provided as template parameter.
- If no Layout is given, derived from the execution space associated with the memory space.
- Defaults are good if you parallelize over left most index!

```cpp
View<int**, LayoutLeft> a("A", N, M);
View<int**, LayoutRight> b("B", N, M);

parallel_for("Fill", N, KOKKOS_LAMBDA(int i) {
    for(int j = 0; j < M; j++) {
        a(i,j) = i * 1000 + j; // coalesced
        b(i,j) = i * 1000 + j; // cached
    }
});
```
Advanced Reductions

- **parallel_reduce** defaults to summation
- Kokkos reducers can be used to reduce over arbitrary operations
- Reductions over multiple values are supported
- Only reductions into scalar arguments are guaranteed to be synchronous

```cpp
parallel_reduce("Join", n,
    KOKKOS_LAMBDA(int i, double& a, int& b) {
        int idx = foo();
        if(idx > b) b = idx;
        a += bar();
    }, result, Kokkos::Max<int>{my_max});
```
### MultiDimensional Loops
How to parallelize tightly nested loops using the MDRangePolicy?

### Subviews and Unmanaged Views
How to get slices of Views, View assignment rules and interoperating with external memory.

### DualView
Managing data synchronization without global understanding of data flow.
Tightly Nested Loops with MDRangePolicy

Learning objectives:
- Demonstrate usage of the MDRangePolicy with tightly nested loops.
- Syntax - Required and optional settings
- Code demo and example
Motivating example: Consider the nested for loops:

```cpp
for ( int i = 0; i < N0; ++i )
for ( int j = 0; j < N1; ++j )
for ( int k = 0; k < N2; ++k )
some_initFcn(i, j, k);
```

Based on Kokkos lessons thus far, you might parallelize this as

```cpp
Kokkos::parallel_for("Label", N0,
    KOKKOS_LAMBDA (const i) {
        for ( int j = 0; j < N1; ++j )
        for ( int k = 0; k < N2; ++k )
            some_initFcn(i, j, k);
    });
```

- This only parallelizes along one dimension, leaving potential parallelism unexploited.
- What if Ni is too small to amortize the cost of constructing a parallel region, but Ni*Nj*Nk makes it worthwhile?
OpenMP has a solution: the collapse clause

```c
#pragma omp parallel for collapse(3)
for (int64_t i = 0; i < N0; ++i) {
    for (int64_t j = 0; j < N1; ++j) {
        for (int64_t k = 0; k < N2; ++k) {
            /* loop body */
        }
    }
}
```
OpenMP has a solution: the collapse clause

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for (int64_t i = 0; i < N0; ++i) {
    for (int64_t j = 0; j < N1; ++j) {
        for (int64_t k = 0; k < N2; ++k) {
            /* loop body */
        }
    }
}
```

Note this changed the policy by adding a ‘collapse‘ clause.
OpenMP has a solution: the collapse clause

```c
#pragma omp parallel for collapse(3) for (int64_t i = 0; i < N0; ++i) {
    for (int64_t j = 0; j < N1; ++j) {
        for (int64_t k = 0; k < N2; ++k) {
/* loop body */
        }
    }
}
```

Note this changed the policy by adding a ‘collapse‘ clause.

With Kokkos you also change the policy:

```c
parallel_for("L", MDRangePolicy<Rank<3>>({0,0,0},{N0,N1,N2}),
    KOKKOS_LAMBDA(int64_t i, int64_t j, int64_t k) {
/* loop body */
});
```
MDRangePolicy can parallelize tightly nested loops of 2 to 6 dimensions.

```cpp
parallel_for("L", MDRangePolicy<Rank<3>>({0,0,0},{N0,N1,N2}),
        KOKKOS_LAMBDA(int64_t i, int64_t j, int64_t k) {
            /* loop body */
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```
MDRangePolicy can parallelize tightly nested loops of 2 to 6 dimensions.

```cpp
parallel_for("L", MDRangePolicy<Rank<3>>({0, 0, 0}, {N0, N1, N2}),
    KOKKOS_LAMBDA(int64_t i, int64_t j, int64_t k) {
        /* loop body */
    });
```

- Specify the dimensionality of the loop with `Rank < DIM >`. 
MDRangePolicy

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parallel_for("L", MDRangePolicy<Rank<3>>({0,0,0},{N0,N1,N2}),
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MDRangePolicy can parallelize tightly nested loops of 2 to 6 dimensions.

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parallel_for("L", MDRangePolicy<Rank<3>>({0, 0, 0}, {N0, N1, N2}),
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            /* loop body */
        });
```

- Specify the dimensionality of the loop with `Rank < DIM >`.
- Provide initializer lists for begin and end values.
MDRangePolicy

MDRangePolicy can parallelize tightly nested loops of 2 to 6 dimensions.

```cpp
parallel_for("L", MDRangePolicy<Rank<3>>({0,0,0},{N0,N1,N2}),
    KOKKOS_LAMBDA(int64_t i, int64_t j, int64_t k) {
        /* loop body */
    });
```

- Specify the dimensionality of the loop with `Rank < DIM`.
- Provide initializer lists for begin and end values.
- The functor/lambda takes matching number of indices.
You can also do Reductions:

```c++
double result;
parallel_reduce("Label",
MDRangePolicy<Rank<3>>({0,0,0},{N0,N1,N2}),
KOKKOS_LAMBDA(int i, int j, int k, double& lsum) {
    /* loop body */
    lsum += something;
}, result);
```

The Policy doesn't change the rules for 'parallel reduce'.

Additional Thread Local Argument.

Can do other reductions with reducers.

Can use 'View's as reduction argument.
You can also do Reductions:

```cpp
double result;
parallel_reduce("Label",
    MDRangePolicy<Rank<3>>({0,0,0},{N0,N1,N2}),
    KOKKOS_LAMBDA(int i, int j, int k, double & lsum) {
        /* loop body */
        lsum += something;
    }, result);
```

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You can also do Reductions:

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double result;
parallel_reduce("Label",
MDRangePolicy<Rank<3>>({0,0,0},{N0,N1,N2}),
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▶ Additional Thread Local Argument.
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        lsum += something;
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```

- The Policy doesn’t change the rules for ‘parallel_reduce’.
- Additional Thread Local Argument.
- Can do other reductions with reducers.
- Can use ‘View’s as reduction argument.
In structured grid applications a **tiling** strategy is often used to help with caching.

MDRangePolicy uses a tiling strategy for the iteration space.

- Specified as a third initializer list.
- For GPUs a tile is handled by a single thread block.
  - If you provide too large a tile size this will fail!

```cpp
double result;
parallel_reduce("Label",
    MDRangePolicy<Rank<3>>({0,0,0},{N0,N1,N2},{T0,T1,T2}),
    KOKKOS_LAMBDA(int i, int j, int k, double & lsum) {
        /* loop body */
        lsum += something;
    }, result);
```
Initializing a Matrix:

```cpp
View<double**, LayoutLeft> A("A", N0, N1);
parallel_for("Label",
    MDRangePolicy<Rank<2>>({0,0},{N0,N1}),
    KOKKOS_LAMBDA(int i, int j) {
        A(i,j) = 1000.0 * i + 1.0*j;
    });

View<double**, LayoutRight> B("B", N0, N1);
parallel_for("Label",
    MDRangePolicy<Rank<2>>({0,0},{N0,N1}),
    KOKKOS_LAMBDA(int i, int j) {
        B(i,j) = 1000.0 * i + 1.0*j;
    });
```

How do I make sure that I get the right access pattern?
Initializing a Matrix:

View<double**>, LayoutLeft > A("A", N0, N1);
parallel_for("Label",
    MDRangePolicy<Rank<2>>({0,0},{N0,N1}),
    KOKKOS_LAMBDA(int i, int j) {
        A(i,j) = 1000.0 * i + 1.0*j;
    });

View<double**>, LayoutRight > B("B", N0, N1);
parallel_for("Label",
    MDRangePolicy<Rank<2>>({0,0},{N0,N1}),
    KOKKOS_LAMBDA(int i, int j) {
        B(i,j) = 1000.0 * i + 1.0*j;
    });

**How do I make sure that I get the right access pattern?**
Iteration Pattern

MDRangePolicy provides compile time control over iteration patterns.

Kokkos::Rank< N, IterateOuter, IterateInner >

- **N**: *(Required)* the rank of the index space (limited from 2 to 6)
- **IterateOuter** *(Optional)* iteration pattern between tiles
  - Options: Iterate::Left, Iterate::Right, Iterate::Default
- **IterateInner** *(Optional)* iteration pattern within tiles
  - Options: Iterate::Left, Iterate::Right, Iterate::Default
Initializing a Matrix fast:

View<
  double**,
  LayoutLeft>
 A("A", N0, N1);
parallel_for("Label",
    MDRangePolicy<
      Rank<2, Iterate::Left, Iterate::Left>>(
      {0,0},{N0,N1}),
    KOKKOS_LAMBDA(int i, int j) {
      A(i,j) = 1000.0 * i + 1.0*j;
    });

View<
  double**,
  LayoutRight>
 B("B", N0, N1);
parallel_for("Label",
    MDRangePolicy<
      Rank<2, Iterate::Right, Iterate::Right>>(
      {0,0},{N0,N1}),
    KOKKOS_LAMBDA(int i, int j) {
      B(i,j) = 1000.0 * i + 1.0*j;
    });
Initializing a Matrix fast:

View< double**, LayoutLeft > A("A", N0, N1);
parallel_for("Label",
    MDRangePolicy<Rank<2, Iterate::Left, Iterate::Left>>(
        {0,0},{N0,N1}),
    KOKKOS_LAMBDA (int i, int j) {
        A(i,j) = 1000.0 * i + 1.0* j;
    });

View< double**, LayoutRight > B("B", N0, N1);
parallel_for("Label",
    MDRangePolicy<Rank<2, Iterate::Right, Iterate::Right>>(
        {0,0},{N0,N1}),
    KOKKOS_LAMBDA (int i, int j) {
        B(i,j) = 1000.0 * i + 1.0* j;
    });

Default Patterns Match

Default iteration patterns match the default memory layouts!
Exercise - mdrange: Initialize multi-dim views with MDRangePolicy

Details:

▶ Location: Exercises/mdrange/Begin/

▶ This begins with the Solution of 02

▶ Initialize the device Views x and y directly on the device using a parallel for and RangePolicy

▶ Initialize the device View matrix A directly on the device using a parallel for and MDRangePolicy

# Compile for CPU
make -j KOKKOS_DEVICES=OpenMP
# Compile for GPU (we do not need UVM anymore)
make -j KOKKOS_DEVICES=Cuda
# Run on GPU
./mdrange_exercise.cuda -S 26
Template Parameters common to ALL policies.

- ExecutionSpace: control where code executes
  - **Options**: Serial, OpenMP, Threads, Cuda, HIP, ...

- Schedule<Options>: set scheduling policy.
  - **Options**: Static, Dynamic

- IndexType<Options>: control internal indexing type
  - **Options**: int, long, etc

- WorkTag: enables multiple operators in one functor

```cpp
struct Foo {
    struct Tag1{}; struct Tag2{};
    KOKKOS_FUNCTION void operator(Tag1, int i) const {...}
    KOKKOS_FUNCTION void operator(Tag2, int i) const {...}
    void run_both(int N) {
        parallel_for(RangePolicy<Tag1>(0,N),*this);
        parallel_for(RangePolicy<Tag2>(0,N),*this);
    }
};
```
MDRangePolicy

- allows for tightly nested loops similar to OpenMP’s collapse clause.
- requires functors/lambdas with as many parameters as its rank is.
- works with `parallel_for` and `parallel_reduce`.
- uses a tiling strategy for the iteration space.
- provides compile time control over iteration patterns.
Subviews: Taking slices of Views

Learning objectives:
- Introduce Kokkos::subview—basic capabilities and syntax
- Suggested usage and practices
- View assignment rules
Sometimes you have to call functions on a subset of data:
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Example: call a frobenius norm on a matrix slice of a rank-3 tensor:

double special_norm(View<double***> tensor, int i) {
    auto matrix = ???;
    // Call a function that takes a matrix:
    return some_library::frobenius_norm(matrix);
}
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Example: call a frobenius norm on a matrix slice of a rank-3 tensor:

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double special_norm(View<double***> tensor, int i) {
    auto matrix = ???;
    // Call a function that takes a matrix:
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}
```

In Fortran or Matlab or Python you can get such a slice:

```cpp
tensor(i,:,:)
```
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Example: call a frobenius norm on a matrix slice of a rank-3 tensor:

```cpp
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    auto matrix = ???;
    // Call a function that takes a matrix:
    return some_library::frobenius_norm(matrix);
}
```

In Fortran or Matlab or Python you can get such a slice:

```cpp
tensor(i,:,:)
```

Kokkos can do that too!

---

**Subview**

*Kokkos::subview* can be used to get a view to a subset of an existing *View*. 
Subview description:

- A subview is a “slice” of a View
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  - The function template Kokkos::subview() takes a View and a slice for each dimension and returns a View of the appropriate shape.
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  - The subview and original View point to the same data—no extra memory allocation nor copying.
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- Can be constructed on host or within a kernel, since no allocation of memory occurs
Subview description:

- A subview is a “slice” of a View
  - The function template Kokkos::subview() takes a View and a slice for each dimension and returns a View of the appropriate shape.
  - The subview and original View point to the same data—no extra memory allocation nor copying
- Can be constructed on host or within a kernel, since no allocation of memory occurs
- Similar capability as provided by Matlab, Fortran, Python, etc., using “colon” notation
Introductory Usage Demo:

Given a View:

```cpp
Kokkos::View<double***> v("v", N0, N1, N2);
```

Say we want a 2-dimensional slice at an index $i_0$ in the first dimension—that is, in Matlab/Fortran/Python notation:

```
slice_{i_0} = v(i_0, :, :);
```

This can be accomplished in Kokkos using a subview as follows:

```cpp
auto sv_{i_0} = Kokkos::subview(v, i0, Kokkos::ALL, Kokkos::ALL);
```

// Just like in Python, you can do the same thing with
// the equivalent of v(i0, 0:N1, 0:N2)
auto sv_{i_0} other = Kokkos::subview(v, i0, Kokkos::make_pair(0, N1), Kokkos::make_pair(0, N2));
Introductory Usage Demo:

Given a View:

```cpp
Kokkos::View<double***> v("v", N0, N1, N2);
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Say we want a 2-dimensional slice at an index \(i_0\) in the first
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```cpp
slicei0 = v(i0, :, :);
```
Introductory Usage Demo:

Given a View:

```cpp
Kokkos::View<double***> v("v", N0, N1, N2);
```

Say we want a 2-dimensional slice at an index i0 in the first dimension—that is, in Matlab/Fortran/Python notation:

```cpp
slice_i0 = v(i0, :, :);
```

This can be accomplished in Kokkos using a subview as follows:

```cpp
auto sv_i0 = 
    Kokkos::subview(v, i0, Kokkos::ALL, Kokkos::ALL);
```

// Just like in Python, you can do the same thing with
// the equivalent of v(i0, 0:N1, 0:N2)
auto sv_i0_other = 
    Kokkos::subview(v, i0, Kokkos::make_pair(0, N1), 
                    Kokkos::make_pair(0, N2));
Subview can take three types of slice arguments:

- **Index**
  - For every index $i$ the rank of the resulting View is decreased by one.
  - Must be between $0 \leq i < \text{extent}(\text{dim})$

- **Kokkos::pair**
  - References a half-open range of indices.
  - The begin and end must be within the extents of the original view.

- **Kokkos::ALL**
  - References the entire extent in that dimension.
  - Equivalent to providing `make_pair(0, v.extent(dim))`
Usage notes:

- Use `auto` for the type of a subview (unless you can’t)

- The return type of `Kokkos::subview()` is implementation defined for performance reasons.

- You can also use `decltype(subview(/*...*/))` if you really need to spell name of the type somewhere.

- Use `Kokkos::pair` for partial ranges if subview created within a kernel.

- Constructing subviews in inner loop code can have performance implications (for now...).

- This will likely be far less of an issue in the future.

- Prioritize readability and maintainability first, then make changes only if you see a performance impact.
Usage notes:

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- Constructing subviews in inner loop code can have performance implications (for now...)
  - This will likely be far less of an issue in the future.
  - Prioritize readability and maintainability first, then make changes only if you see a performance impact.
Details:

- Location: Exercises/subview/Begin/
- This begins with the Solution of 04
- In the parallel reduce kernel, create a subview for row $j$ of view $A$
- Use this subview when computing $A(j,:)^\times x(:)$ rather than the matrix $A$

```bash
# Compile for CPU
make -j KOKKOS_DEVICES=OpenMP
# Compile for GPU (we do not need UVM anymore)
make -j KOKKOS_DEVICES=Cuda
# Run on GPU
./subview_exercise.cuda -S 26
```
View::operator=() just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4)
View::operator=() just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
View::operator=() just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
- View<int*[5]> a; a = View<int**>("b", 4, 5)
View::operator=() just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
- View<int*[5]> a; a = View<int**>("b", 4, 5) => Okay, checked at runtime
View::operator=( ) just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
- View<int*[5]> a; a = View<int**>("b", 4, 5) => Okay, checked at runtime
- View<int*[5]> a; a = View<int*[3]>("b", 4)
View::operator=(...) just does the “Right Thing”™

- `View<int**> a; a = View<int*[5]>("b", 4) => Okay`
- `View<int*[5]> a; a = View<int**>("b", 4, 5) => Okay, checked at runtime`
- `View<int*[5]> a; a = View<int*[3]>("b", 4) => Compilation error`
Aside: View Assignment (1)

View::operator=(...) just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
- View<int*[5]> a; a = View<int**>("b", 4, 5) => Okay, checked at runtime
- View<int*[5]> a; a = View<int*[3]>("b", 4) => Compilation error
- View<int*[5]> a; a = View<int**>("b", 4, 3)
View::operator=() just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
- View<int*[5]> a; a = View<int**>("b", 4, 5) => Okay, checked at runtime
- View<int*[5]> a; a = View<int*[3]>("b", 4) => Compilation error
- View<int*[5]> a; a = View<int**>("b", 4, 3) => Runtime error
View::operator=(...) just does the “Right Thing”\textsuperscript{TM}

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
- View<int*[5]> a; a = View<int**>("b", 4, 5) => Okay, checked at runtime
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- View<int*[5]> a; a = View<int**>("b", 4, 3) => Runtime error
- View<int*, CudaSpace> a;
a = View<int*, HostSpace>("b", 4)
Aside: View Assignment (1)

View::operator=( ) just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
- View<int*[5]> a; a = View<int**>("b", 4, 5) => Okay, checked at runtime
- View<int*[5]> a; a = View<int*[3]>("b", 4) => Compilation error
- View<int*[5]> a; a = View<int**>("b", 4, 3) => Runtime error
- View<int*, CudaSpace> a;
  a = View<int*, HostSpace>("b", 4) => Compilation error
- View<int**, LayoutLeft> a;
  a = View<int**, LayoutRight>("b", 4, 5)
Aside: View Assignment (1)

View::operator=() just does the “Right Thing”™

- View<int**> a; a = View<int*[5]>("b", 4) => Okay
- View<int*[5]> a; a = View<int**>("b", 4, 5) => Okay, checked at runtime
- View<int*[5]> a; a = View<int*[3]>("b", 4) => Compilation error
- View<int*[5]> a; a = View<int**>("b", 4, 3) => Runtime error
- View<int*, CudaSpace> a;
  a = View<int*, HostSpace>("b", 4) => Compilation error
- View<int**, LayoutLeft> a;
  a = View<int**, LayoutRight>("b", 4, 5) => Compilation error
View::operator=() just does the “Right Thing”™

- View<const int*> a; a = View<int*>("b", 4)
View::operator=( ) just does the “Right Thing”™

▶ View<const int*> a; a = View<int*>("b", 4) 
  => Okay
View::operator=( ) just does the “Right Thing”™

- View<const int*> a; a = View<int*>("b", 4) => Okay
- View<int*> a; a = View<const int*>("b", 4)
View::operator=() just does the “Right Thing”™

- View<const int*> a; a = View<int*>("b", 4)  
  => Okay

- View<int*> a; a = View<const int*>("b", 4)  
  => Compilation error
View::operator=() just does the “Right Thing”™

- View<const int*> a; a = View<int*>("b", 4)  
  => Okay

- View<int*> a; a = View<const int*>("b", 4)  
  => Compilation error

- View<int*[5], LayoutStride> a;  
  a = View<int*[5], LayoutLeft>("b", 4)
View::operator=(...) just does the “Right Thing”™

- View<const int*> a; a = View<int*>("b", 4) => Okay
- View<int*> a; a = View<const int*>("b", 4) => Compilation error
- View<int*[5], LayoutStride> a;
  a = View<int*[5], LayoutLeft>("b", 4) => Okay,
  converting compile-time strides into runtime strides
View::operator=() just does the “Right Thing”™

- View<const int*> a; a = View<int*>("b", 4)
  => Okay

- View<int*> a; a = View<const int*>("b", 4)
  => Compilation error

- View<int*[5], LayoutStride> a;
  a = View<int*[5], LayoutLeft>("b", 4) => Okay,
  converting compile-time strides into runtime strides

- View<int*[5], LayoutLeft> a;
  a = View<int*[5], LayoutStride>("b", 4)
View::operator=() ***just does the “Right Thing”***

- View<const int*>& a; a = View<int*>("b", 4) => Okay
- View<int*> a; a = View<const int*>("b", 4) => Compilation error
- View<int*[5], LayoutStride> a; a = View<int*[5], LayoutLeft>("b", 4) => Okay, converting compile-time strides into runtime strides
- View<int*[5], LayoutLeft> a; a = View<int*[5], LayoutStride>("b", 4) => Okay, but only if strides match layout left (checked at runtime)
Given a View:

Kokkos::View<int***> v("v", n0, n1, n2);

View<int***> a;

a = Kokkos::subview(v, ALL, 42, ALL);
Given a View:

```cpp
Kokkos::View<int***> v("v", n0, n1, n2);

View<int***> a;
```n a = Kokkos::subview(v, ALL, 42, ALL);

=> Compilation error
Given a View:

```
Kokkos::View<int***> v("v", n0, n1, n2);

View<int***> a;
a = Kokkos::subview(v, ALL, 42, ALL);
=> Compilation error
```

```
View<int*> a;
a = Kokkos::subview(v, ALL, 5, 42);
```

Runtime error (!)
Given a View:

```cpp
Kokkos::View<int***> v("v", n0, n1, n2);
```

- `View<int***> a;`  
  ```cpp
  a = Kokkos::subview(v, ALL, 42, ALL);
  ```  
  => **Compilation error**

- `View<int**> a;`  
  ```cpp
  a = Kokkos::subview(v, ALL, 15, ALL);
  ```  
  => **Runtime error (!)**

- `View<int**, LayoutStride> a;`  
  ```cpp
  a = Kokkos::subview(v, ALL, 15, ALL);
  ```  
  => **Okay**
Given a View:

```
Kokkos::View<int***> v("v", n0, n1, n2);

- View<int***> a;
  a = Kokkos::subview(v, ALL, 42, ALL);
  => Compilation error

- View<int*> a;
  a = Kokkos::subview(v, ALL, 5, 42);
  => Okay for LayoutLeft but => Compilation error for LayoutRight

- View<int**> a;
  a = Kokkos::subview(v, ALL, 15, ALL);
```
Given a View:

```cpp
Kokkos::View<int***> v("v", n0, n1, n2);
```

- View<int***> a;
  ```cpp
  a = Kokkos::subview(v, ALL, 42, ALL);
  ```
  => Compilation error

- View<int*> a;
  ```cpp
  a = Kokkos::subview(v, ALL, 5, 42);
  ```
  => Okay for LayoutLeft but => Compilation error for LayoutRight

- View<int**> a;
  ```cpp
  a = Kokkos::subview(v, ALL, 15, ALL);
  ```
  => Runtime error (!)
Given a View:

```
Kokkos::View<int**> v("v", n0, n1, n2);
```

- **View<int***> a;
  a = Kokkos::subview(v, ALL, 42, ALL);
  => Compilation error

- **View<int*> a;
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  => Runtime error (!)

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Given a View:

Kokkos::View<int***> v("v", n0, n1, n2);

- View<int***> a;
  a = Kokkos::subview(v, ALL, 42, ALL);
  => Compilation error

- View<int*> a;
  a = Kokkos::subview(v, ALL, 5, 42);
  => Okay for LayoutLeft but => Compilation error for LayoutRight

- View<int**> a;
  a = Kokkos::subview(v, ALL, 15, ALL);
  => Runtime error (!)

- View<int**, LayoutStride> a;
  a = Kokkos::subview(v, ALL, 15, ALL);
  => Okay
Use subviews to get a portion of a `View`. Helps with:

- code reuse
- code readability
- library function compatibility
Use subviews to get a portion of a View. Helps with:
- code reuse
- code readability
- library function compatibility

Kokkos supports slicing Views similar to Python/Matlab/Fortran slicing syntax

```cpp
auto sv = Kokkos::subview(v, 42, ALL, std::make_pair(3, 17));
```
Use subviews to get a portion of a View. Helps with:
  - code reuse
  - code readability
  - library function compatibility

Kokkos supports slicing Views similar to Python/Matlab/Fortran slicing syntax

```cpp
auto sv = Kokkos::subview(v, 42, ALL, std::make_pair(3, 17));
```

The return type of `subview` is complicated. Use `auto`!!

`View::operator=()` just does the “Right Thing”™
  - So generally don’t worry about it at first! This is advanced stuff, and more for future reference.
Unmanaged Views: Dealing with external memory

Learning objectives:

▶ Why do you need unmanaged views
▶ Introduce unmanaged Views - basic capabilities and syntax
▶ Suggested usage and practices
Sometimes your Kokkos code can’t control all allocations!

- Obviously best to avoid that unpleasant situation ...

But say you use some external function like IO classes:

```cpp
struct MatrixReader {
  int N, M;
  std::vector<double> values;
  void read_file(std::string name) {...}
};
```
Sometimes your Kokkos code can’t control all allocations!

- Obviously best to avoid that unpleasant situation ...

But say you use some external function like IO classes:

```cpp
struct MatrixReader {
    int N, M;
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```

How can you get this to the GPU without extra allocation?
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But say you use some external function like IO classes:

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    int N, M;
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```

How can you get this to the GPU without extra allocation?

**Unmanaged Views**

Views can wrap existing allocations as Unmanaged Views.
Unmanaged View description:

- Normally, Views allocate memory and manage.
- Instead, Views can use externally controlled memory
Unmanaged View description:

- Normally, Views allocate memory and manage.
- Instead, Views can use externally controlled memory.
- Caveats
  - No reference counting
  - No deallocation in the constructor
  - No check for the correct memory space
- Usages
  - Layout-punning: e.g., treat multidimensional View as one-dimensional views without copying
  - Use `std::vector` or memory from CUDA library, e.g. cuSPARSE
Back to our IO example:

```cpp
struct MatrixReader {
    int N, M;
    std::vector<double> values;
    void read_file(std::string name) {...}
};
```

To create an unmanaged View:

- Provide a pointer as the first constructor argument.
- Give all the runtime dimensions.
- Make sure Layout and MemorySpace match!
- Unmanaged Views do NOT get a label!

```cpp
MatrixReader reader; reader.read_file("MM");
View<double **, LayoutRight, HostSpace> h_a(reader.values.data(), reader.N, reader.M);
```

How do we get this to the device?
Back to our IO example:

```cpp
struct MatrixReader {
    int N, M;
    std::vector<double> values;
    void read_file(std::string name) {...}
};
```

To create an unmanaged View:

- Provide a pointer as the first constructor argument.
- Give all the runtime dimensions.
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- Unmanaged Views do NOT get a label!

```cpp
MatrixReader reader; reader.read_file("MM");
View<double**, LayoutRight, HostSpace>
    h_a(reader.values.data(), reader.N, reader.M);
```
Back to our IO example:

```cpp
struct MatrixReader {
    int N, M;
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```cpp
MatrixReader reader; reader.read_file("MM");
View<double**, LayoutRight, HostSpace>
    h_a(reader.values.data(), reader.N, reader.M);
```

How do we get this to the device?
In Module 2 we learned the Mirror Pattern

- But the mirror pattern started with a device view!
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- But the mirror pattern started with a device view!

### Mirror in any Space

`Kokkos::create_mirror_view` can take a space argument for location of mirror.
In Module 2 we learned the Mirror Pattern

- But the mirror pattern started with a device view!

Mirror in any Space

Kokkos::create_mirror_view can take a space argument for location of mirror.

```cpp
// Create mirror into default memory space
using space_t = DefaultExecutionSpace::memory_space;
auto a = create_mirror_view(space_t(), h_a);
// Copy values from the host to the device
depth_copy(a, h_a);
```
In Module 2 we learned the Mirror Pattern

- But the mirror pattern started with a device view!

## Mirror in any Space

Kokkos::create_mirror_view can take a space argument for location of mirror.

```cpp
// Create mirror into default memory space
using space_t = DefaultExecutionSpace::memory_space;
auto a = create_mirror_view(space_t(), h_a);
// Copy values from the host to the device
deep_copy(a, h_a);
```

Since the “create mirror and then copy” pattern is common we have a shortcut:

```cpp
auto a = create_mirror_view_and_copy(space_t(), h_a);
```
Using pre-allocated scratch memory for temporary data structures is common to:

▶ Eliminate costly allocation/deallocation operations
▶ Reduce total memory footprint.
Using pre-allocated scratch memory for temporary data structures is common to:

▶ Eliminate costly allocation/deallocation operations
▶ Reduce total memory footprint.

Unmanaged Views of Scratch Allocations

Unmanaged Views can be used to get arrays of different shapes backed by the same memory.

```c
void* scratch = kokkos_malloc<"Scratch", scratch_size>();
View<double**> a_scr(scratch, N,M);
View<int*> b_scr(scratch,K);
```
Using pre-allocated scratch memory for temporary data structures is common to:

- Eliminate costly allocation/deallocation operations
- Reduce total memory footprint.

Unmanaged Views of Scratch Allocations

Unmanaged Views can be used to get arrays of different shapes backed by the same memory.

```c
void* scratch = kokkos_malloc<>("Scratch", scratch_size);
View<double**> a_scr(scratch, N,M);
View<int*> b_scr(scratch,K);
```

How much memory do you need for a View?

```c
int scratch_size = View<double**>::required_allocation_size(N,M);
```
Unmanaged Views Summary

- Unmanaged Views wrap existing allocations
  - No ref-counting
  - No deallocation after losing scope
  - No memory space checks

```c
void * ptr = kokkos_malloc < >(" Alloc ", alloc_size);
View < double ** > h_a (( double *) ptr ,N,M);
```
Unmanaged Views Summary

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- Unmanaged view is created with pointer and runtime dimensions
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  - No ref-counting
  - No deallocation after losing scope
  - No memory space checks
- Unmanaged view is created with pointer and runtime dimensions
  
  ```c
  void* ptr = kokkos_malloc<>("Alloc", alloc_size);
  View<double**> h_a((double*)ptr,N,M);
  ```
Unmanaged Views wrap existing allocations

- No ref-counting
- No deallocation after losing scope
- No memory space checks

Unmanaged view is created with pointer and runtime dimensions

```c
void* ptr = kokkos_malloc<"Alloc", alloc_size>;
View<double**> h_a((double*)ptr,N,M);
```

Unmanaged view uses

- Access externally controlled memory
- Access temporary scratch memory
- Layout pruning - view underlying data using different layout
Thread safety and atomic operations

Learning objectives:

▶ Understand that coordination techniques for low-count CPU threading are not scalable.

▶ Understand how atomics can parallelize the scatter-add pattern.

▶ Gain performance intuition for atomics on the CPU and GPU, for different data types and contention rates.
Examples: Histogram

Histogram kernel:

```cpp
parallel_for(N, KOKKOS_LAMBDA(const size_t index) {
    const Something value = ...;
    const size_t bucketIndex = computeBucketIndex(value);
    ++_histogram(bucketIndex);
});
```

Problem: Multiple threads may try to write to the same location.

Solution strategies:
- Locks: not feasible on GPU
- Thread-private copies: not thread-scalable
- Atomics

http://www.farmaceuticas.com.br/tag/graficos/
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**Problem:** Multiple threads may try to write to the same location.

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- Locks: not feasible on GPU
- Thread-private copies: not thread-scalable
- Atomics

http://www.farmaceuticas.com.br/tag/graficos/
**Atomics**: the portable and thread-scalable solution

```cpp
parallel_for(N, KOKKOS_LAMBDA(const size_t index) {
    const Something value = ...;
    const int bucketIndex = computeBucketIndex(value);
    Kokkos::atomic_add(&_histogram(bucketIndex), 1);
});
```

Atomics are the only scalable solution to thread safety. Locks are not portable. Data replication is not thread scalable.
Atomics: the portable and thread-scalable solution

```cpp
parallel_for(N, KOKKOS_LAMBDA(const size_t index) {
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Atomics: the portable and thread-scalable solution

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- Locks are **not portable**.
**Atomics**: the portable and thread-scalable solution

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});
```

- Atomics are the **only scalable** solution to thread safety.
- Locks are **not portable**.
- Data replication is **not thread scalable**.
How expensive are atomics?

Thought experiment: scalar integration

```cpp
operator()(const unsigned int intervalIndex,
           double & valueToUpdate) const {
    double contribution = function(...);
    valueToUpdate += contribution;
}
```

Idea: what if we instead do this with parallel for and atomics?

```cpp
operator()(const unsigned int intervalIndex) const {
    const double contribution = function(...);
    Kokkos::atomic_add(& globalSum, contribution);
}
```
How expensive are atomics?

Thought experiment: scalar integration

```cpp
operator()(const unsigned int intervalIndex, 
    double & valueToUpdate) const {
    double contribution = function(...);
    valueToUpdate += contribution;
}
```

Idea: what if we instead do this with parallel_for and atomics?

```cpp
operator()(const unsigned int intervalIndex) const {
    const double contribution = function(...);
    Kokkos::atomic_add(&globalSum, contribution);
}
```

How much of a performance penalty is incurred?
**Two costs:** (independent) **work** and **coordination**.

```cpp
parallel_reduce(numberOfIntervals,
    KOKKOS_LAMBDA (const unsigned int intervalIndex,
        double & valueToUpdate) {
        valueToUpdate += function(...);
    }, totalIntegral);
```

▶ This is the most extreme case: all coordination and no work.
▶ Contention is captured by the `atomicStride`.

- `atomicStride → 1` ⇒ Scalar integration (bad)
- `atomicStride → large` ⇒ Independent (good)
Two costs: (independent) work and coordination.

Parallel reduce:
```
parallel_reduce(numberOfIntervals, 
    KOKKOS_LAMBDA (const unsigned int intervalIndex, 
                   double & valueToUpdate) {
        valueToUpdate += function(...);
    }, totalIntegral);
```

Experimental setup
```
operator()(const unsigned int index) const {
    Kokkos::atomic_add(&globalSums[index % atomicStride], 1);
}
```

▶ This is the most extreme case: all coordination and no work.
▶ Contention is captured by the atomicStride.
  atomicStride → 1  ⇒ Scalar integration (bad)
  atomicStride → large ⇒ Independent (good)
Atomics performance: 1 million adds, **no work per kernel**

Slowdown from atomics: Summary for 1 million adds, mod, 0 pows

![Graph showing slowdown from atomics](image)

**Note:** log scale

- **cuda double**
- **cuda uint64_t**
- **cuda float**
- **cuda unsigned**
- **omp double**
- **omp size_t**
- **omp float**
- **omp unsigned**
- **phi double**
- **phi size_t**
- **phi float**
- **phi unsigned**
Atoms performance: 1 million adds, no work per kernel

Slowdown from atomics: Summary for 1 million adds, mod, 0 pows

Note: log scale

Low(?) penalty for low contention

High penalty for high contention

log10(speedup over independent) [-]

log10(contention) [-]
**Performance of atomics (3)**

Atomics per some work per kernel:

- 1 million adds
- Log scale
- No penalty for low contention
- High penalty for high contention

---

![Graph showing slowdown from atomics: Summary for 1 million adds, mod, 2 pows](image)

- Log scale for contentions
- Log scale for speedup over independent
Performance of atomics: 1 million adds, lots of work per kernel

Slowdown from atomics: Summary for 1 million adds, mod, 5 pows

Note: log scale

No penalty for low contention

High penalty for high contention

- cuda double
- cuda uint64_t
- cuda float
- cuda unsigned
- omp double
- omp size_t
- omp float
- omp unsigned
- phi double
- phi size_t
- phi float
- phi unsigned
Atomics on arbitrary types:

- Atomic operations work if the corresponding operator exists, i.e., `atomic_add` works on any data type with "+".
- Atomic exchange works on any data type.

```cpp
// Assign *dest to val, return former value of *dest
template<typename T>
T atomic_exchange(T * dest, T val);
// If *dest == comp then assign *dest to val
// Return true if succeeds.
template<typename T>
bool atomic_compare_exchange_strong(T * dest, T comp, T val);
```
Slight detour: View memory traits:

- Beyond a Layout and Space, Views can have memory traits.
- Memory traits either provide convenience or allow for certain hardware-specific optimizations to be performed.

Example: If all accesses to a View will be atomic, use the Atomic memory trait:

```cpp
View<double**, Layout, Space, MemoryTraits<Atomic>> > forces(...);
```
Slight detour: View memory traits:

- Beyond a Layout and Space, Views can have memory traits.
- Memory traits either provide **convenience** or allow for certain **hardware-specific optimizations** to be performed.

Example: If all accesses to a View will be atomic, use the Atomic memory trait:

```
View<double**, Layout, Space,
    MemoryTraits<Atomic> > forces(...);
```

Many memory traits exist or are experimental, including Atomic, Unmanaged, Restrict, and RandomAccess.
**Example: RandomAccess memory trait:**

On **GPUs**, there is a special pathway for fast **read-only, random** access, originally designed for textures.
Example: RandomAccess memory trait:

On GPUs, there is a special pathway for fast read-only, random access, originally designed for textures.

In the early days you had to access this via CUDA:

```c
cudaResourceDesc resDesc;
memset(&resDesc, 0, sizeof(resDesc));
resDesc.resType = cudaResourceTypeLinear;
resDesc.res.linear.devPtr = buffer;
resDesc.res.linear.desc.f = cudaChannelFormatKindFloat;
resDesc.res.linear.desc.x = 32; // bits per channel
resDesc.res.linear.sizeInBytes = N*sizeof(float);

cudaTextureDesc texDesc;
memset(&texDesc, 0, sizeof(texDesc));
texDesc.readMode = cudaReadModeElementType;

cudaTextureObject_t tex=0;
cudaCreateTextureObject(&tex, &resDesc, &texDesc, NULL);
```
Example: RandomAccess memory trait:

On GPUs, there is a special pathway for fast read-only, random access, originally designed for textures.

In the early days you had to access this via CUDA:

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memset(&resDesc, 0, sizeof(resDesc));
resDesc.resType = cudaResourceTypeLinear;
resDesc.res.linear.devPtr = buffer;
resDesc.res.linear.desc.f = cudaChannelFormatKindFloat;
resDesc.res.linear.desc.x = 32; /* bits per channel */
resDesc.res.linear.sizeInBytes = N*sizeof(float);

cudaTextureDesc texDesc;
memset(&texDesc, 0, sizeof(texDesc));
texDesc.readMode = cudaReadModeElementType;

cudaTextureObject_t tex=0;
cudaCreateTextureObject(&tex, &resDesc, &texDesc, NULL);
```

Kokkos can hide mechanisms like that as simple as:
```
View< const double***, Layout, Space,
  MemoryTraits<RandomAccess> > name(...);
```
Histogram generation is an example of the **Scatter Contribute** pattern.

- Like a reduction but with many results.
- Number of results scales with number of inputs.
- Each result gets contributions from a small number of inputs/iterations.
- Uses an inputs-to-results map not inverse.

**Examples:**

- Particles contributing to neighbors forces.
- Cells contributing forces to nodes.
- Computing histograms.
- Computing a density grid from point source contributions.
Compute forces on particles via neighbor contributions
This kernel uses Newton's Third Law: Actio = Reactio

```c
void compute_forces(View<real3*> x, View<real3*> f,
                      View<int**> neighs, Interaction force) {
    int N = x.extent(0);
    int num_neighs = neighs.extent(1);
    parallel_for("ForceCompute", N, KOKKOS_LAMBDA(int i) {
        for(int j=0; j<num_neighs; j++) {
            real3 df = force.compute(x(i),x(neighs(i,j)));
            f(i) += df;
            f(j) -= df;
        }
    });
}
```
Compute forces on particles via neighbor contributions
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      f(i) += df;
      f(j) -= df;
    }
  });
}
```

This kernel has a race condition on f though!
There are two useful algorithms:

- **Atomics**: thread-scalable but depends on atomic performance.
- **Data Replication**: every thread owns a copy of the output, not thread-scalable but good for low (< 16) threads count architectures.

Important Capability: ScatterView

ScatterView can transparently switch between Atomic and Data Replication based scatter algorithms.

- Abstracts over scatter contribute algorithms.
- Compile time choice with backend-specific defaults.
- Only limited number of operations are supported.
- Part of Kokkos Containers (in Kokkos 3.2 still experimental).
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▶ Only limited number of operations are supported.
▶ Part of Kokkos Containers (in Kokkos 3.2 still experimental).
Creating a ScatterView:
Usually a ScatterView wraps an existing View

void compute_forces(View<real3 *> x, View<real3 *> f, View<int **> neighs, Interaction force) {
    Kokkos::Experimental::ScatterView<real3 *> scatter_f(f);
    // ...

    Accessing the ScatterView
In the kernel obtain an atomic or thread-local accessor.
parallel_for("ForceCompute", N, KOKKOS_LAMBDA(int i) {
    auto f_a = scatter_f.access();
    for (int j = 0; j < num_neighs; j++) {
        real3 df = force.compute(x(i), x(neighs(i, j)));
        f_a(i) += df;
        f_a(j) -= df;
    }
});

Only the += and -= operators are available!
Creating a ScatterView:
Usually a ScatterView wraps an existing View

- Allows the **atomic** variant to work without extra allocation.

```cpp
void compute_forces (View < real3 *> x, View < real3 *> f, View < int ** > neighs, Interaction force ) {
    Kokkos :: Experimental :: ScatterView < real3 *> scatter_f (f);
    ...
    Accessing the ScatterView
    In the kernel obtain an atomic or thread-local accessor.
    parallel_for ( "ForceCompute", N, KOKKOS_LAMBDA ( int i) {
        auto f_a = scatter_f . access ();
        for ( int j =0; j< num_neighs ; j ++) {
            real3 df = force . compute (x(i),x( neighs (i,j )));
            f_a (i) += df;
            f_a (j) -= df;
        }
    });

    Only the += and -= operators are available!
```
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                      View<int**> neighs, Interaction force) {
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    ...
```
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Accessing the ScatterView

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  auto f_a = scatter_f.access();
  for(int j=0; j<num_neighs; j++) {
    real3 df = force.compute(x(i),x(neighs(i,j)));
    f_a(i) += df;
    f_a(j) -= df;
  }
});
```

Only the `+=` and `-=` operators are available!
We are missing one step though:
We are missing one step though: **Contribute back to the original view.**

```cpp
void compute_forces(View<real3*> x, View<real3*> f,
                      View<int**> neighs, Interaction force) {
    Kokkos::Experimental::ScatterView<real3*> scatter_f(f);
    parallel_for("ForceCompute", N, KOKKOS_LAMBDA(int i) {
        ...}
    Kokkos::Experimental::contribute(f, scatter_f);
```
We are missing one step though: **Contribute back to the original view.**

```cpp
class View { /* ... */ }

void compute_forces(View<real3*> x, View<real3*> f, 
                      View<int**> neighs, Interaction force) {
    Kokkos::Experimental::ScatterView<real3*> scatter_f(f);
    parallel_for("ForceCompute", N, KOKKOS_LAMBDA(int i) { ...
    Kokkos::Experimental::contribute(f, scatter_f);
}
```

- No-op when `scatter_f` uses **atomic** access
- Combines thread-local arrays in case of data duplication
We are missing one step though: **Contribute back to the original view.**

```cpp
void compute_forces(View<real3*> x, View<real3*> f,
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    Kokkos::Experimental::ScatterView<real3*> scatter_f(f);
    parallel_for("ForceCompute", N, KOKKOS_LAMBDA(int i) {
        ...
    });
    Kokkos::Experimental::contribute(f, scatter_f);
}
```

- No-op when `scatter_f` uses **atomic** access
- Combines thread-local arrays in case of data duplication

**Important Point**

Reuse ScatterView if possible: creating and destroying data duplicates is costly and should be avoided
When reusing a ScatterView the duplicates have to be reset.

```cpp
scatter_f.reset();
```
When reusing a ScatterView the duplicates have to be reset.

```
scatter_f.reset();
```

**The complete picture:**

```c++
void compute_forces(View<real3*> x, View<real3*> f,
                     ScatterView<real3*> scatter_f,
                     View<int**> neighs, Interaction force) {

    scatter_f.reset();
    int N = x.extent(0);
    int num_neighs = neighs.extent(1);
    parallel_for("ForceCompute", N, KOKKOS_LAMBDA(int i) {
        auto f_a = scatter_f.access();
        for(int j=0; j<num_neighs; j++) {
            real3 df = force.compute(x(i),x(neighs(i,j)));
            f_a(i) += df;
            f_a(j) -= df;
        }
    });

    Kokkos::Experimental::contribute(f,scatter_f);
}
```
But I need something else than a Sum!
But I need something else than a Sum!
ScatterView has more options including the reduction op.

```
template<class DataType, class Layout, class Space,
        class Operation, int Duplication, int Contribution>
class ScatterView;
```

- **DataType, Layout, Space**: as in Kokkos::View
- **Operation**: ScatterSum, ScatterProd, ScatterMin, or ScatterMax.
- **Duplication**: Whether to duplicate values per thread.
- **Contribution**: Whether to use **atomics**.
Location: Exercises/scatter_view/Begin/

Assignment: Convert scatter_view_loop to use ScatterView.

Compile and run on both CPU and GPU

```make
make -j KOKKOS_DEVICES=OpenMP # CPU-only using OpenMP
make -j KOKKOS_DEVICES=Cuda # GPU - note UVM in Makefile
# Run exercise
./scatterview.host
./scatterview.cuda
# Note the warnings, set appropriate environment variables
```

- Compare performance on CPU of the three variants
- Compare performance on GPU of the two variants
- Vary problem size: first and second optional argument
Atomics are the only thread-scalable solution to thread safety.

- Locks or data replication are **not portable or scalable**

Atomic performance **depends on ratio** of independent work and atomic operations.

- With more work, there is a lower performance penalty, because of increased opportunity to interleave work and atomic.

The Atomic **memory trait** can be used to make all accesses to a view atomic.

The cost of atomics can be negligible:

- **CPU** ideal: contiguous access, integer types
- **GPU** ideal: scattered access, 32-bit types

Many programs with the **scatter-add** pattern can be thread-scalably parallelized using atomics without much modification.
Learning objectives:

▶ Motivation and Value Added.
▶ Usage.
▶ Exercises.
Motivation and Value-added

- DualView was designed to help transition codes to Kokkos.
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- DualView simplifies the task of managing data movement between memory spaces, e.g., host and device.
Motivation and Value-added

- DualView was designed to help transition codes to Kokkos.
- DualView simplifies the task of managing data movement between memory spaces, e.g., host and device.
- When converting a typical app to use Kokkos, there is usually no holistic view of such data transfers.
Without DualView, could use MirrorViews, but

- deep copies are expensive, use sparingly
- do I need a deep copy here?
- where is the most recent data?
- is data on the host or device stale?
- was code modified upstream? is data here now stale, but not in previous version?
DualView bundles two views, a Host View and a Device View

There is no automatic tracking of data freshness:

- you must tell Kokkos when data has been modified on a memory space.
- If you mark data as modified when you modify it, then Kokkos will know if it needs to move data
DualView bundles two views, a Host View and a Device View

- Data members for the two views
  ```
  DualView::t_host h_view
  DualView::t_dev d_view
  ```

- Retrieve data members
  ```
  t_host view_host();
  t_dev  view_device();
  ```

- Mark data as modified
  ```
  void modify_host();
  void modify_device();
  ```
DualView bundles two views, a Host View and a Device View

- Sync data in a direction if not in sync

  ```c
  void sync_host();
  void sync_device();
  ```

- Check sync status

  ```c
  bool need_sync_host();
  bool need_sync_device();
  ```
DualView has templated functions for generic use in templated code

- **Retrieve data members**
  
  ```cpp
  template <class Space>
  auto view();
  ```

- **Mark data as modified**
  
  ```cpp
  template <class Space>
  void modify();
  ```

- **Sync data in a direction if not in sync**
  
  ```cpp
  template <class Space>
  void sync();
  ```

- **Check sync status**
  
  ```cpp
  template <class Space>
  bool need_sync();
  ```
class Foo {
    DualView<...> data;
    void run_a() {
        data.sync_device(); data.modify_device();
        auto d_data = data.view_device();
        parallel_for(N, KOKKOS_LAMBDA(int i) { d_data(i)+= /* mod d_d*/ });
    }
    void run_b() {
        data.sync_host();
        auto h_data = data.view_host();
        for(int i=0; i<N; i++) { h_data(i) += /* modify h_data */};
        data.modify_host();
    }
    void run_c() {
        data.sync_device();
        auto d_data = data.view_device();
        parallel_for(N, KOKKOS_LAMBDA(int i) { /* read d_data */ });
    }
    void do_operations(bool a, bool b, bool c) {
        if(a) run_a();
        if(b) run_b();
        if(c) run_c();
    }
};
Details:

- Location: Exercises/dualview/Begin/
- Modify or create a new compute_enthalpy function in dual_view_exercise.cpp to:
  1. Take (dual)views as arguments
  2. Call `modify()` and/or `sync()` when appropriate for the dual views
  3. Runs the kernel on host or device execution spaces

```
# Compile for CPU
make -j KOKKOS_DEVICES=OpenMP
# Compile for GPU (we do not need UVM anymore)
make -j KOKKOS_DEVICES=Cuda
# Run on GPU
./dualview.cuda -S 26
```
MDRangePolicy

- Tightly nested loops (similar to OpenMP collapse clause)
- Available with parallel_for and parallel_reduce
- Tiling strategy over the iteration space
- Control iteration pattern at compile time

```c++
View<double**, LayoutLeft> A("A", N0, N1);
parallel_for("Label",
    MDRangePolicy<Rank<2, Iterate::Left, Iterate::Left>>(
        {0, 0}, {N0, N1}),
    KOKKOS_LAMBDA(int i, int j) {
        A(i,j) = 1000.0 * i + 1.0*j;
    });
```
Subviews

- Taking slices of Views
- Similar capability as provided by Matlab, Fortran, or Python
- Prefer the use of auto for the type

```cpp
View<int ***> v("v", N0, N1, N2);
auto sv = subview(v, i0, ALL, make_pair(start,end));
```

Unmanaged Views

- Interoperability with externally allocated arrays
- No reference counting, memory not deallocated at destruction
- User is responsible for insuring proper dynamic and/or static extents, MemorySpace, Layout, etc.

```cpp
View<float**, LayoutRight, HostSpace> v_unmanaged(raw_ptr, N0, N1);
```
Atomic operations

- Atomic functions available on the host or the device (e.g. Kokkos::atomic_add)
- Use Atomic memory trait for atomic accesses on Views

```cpp
View<int*> v("v", N0);
View<int*, MemoryTraits<Atomic>> v_atomic = v;
```

- Use ScatterView for scatter-add parallel pattern

Dual Views

- For managing data synchronization between host and device
- Helps in codes with no holistic view of data flow
  - In particular when porting codes incrementally
Hierarchical Parallelism

- How to leverage more parallelism through nested loops.
- The concept of Thread-Teams and Vectorlength.

Scratch Space

- Getting temporary workspace in kernels.
- Leveraging GPU Shared Memory.

Unique Token

- How to acquire safely per-thread resources.

Don’t Forget: Join our Slack Channel and drop into our office hours on Tuesday.

Updates at: bit.ly/kokkos-lecture-updates

Recordings/Slides: bit.ly/kokkos-lecture-wiki