

The Kokkos Lectures

Module 4: Hierarchical Parallelism

April 26, 2024

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.

Hierarchical parallelism

Finding and exploiting more parallelism in your computations.

Learning objectives:

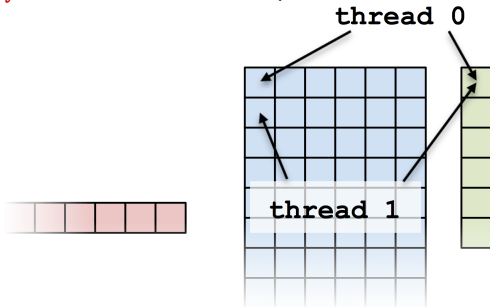
- ▶ Similarities and differences between outer and inner levels of parallelism
- ▶ Thread teams (league of teams of threads)
- ▶ Performance improvement with well-coordinated teams

(Flat parallel) Kernel:

```

Kokkos::parallel_reduce("yAx",N,
  KOKKOS_LAMBDA (const int row, double & valueToUpdate) {
    double thisRowsSum = 0;
    for (int col = 0; col < M; ++col) {
      thisRowsSum += A(row,col) * x(col);
    }
    valueToUpdate += y(row) * thisRowsSum;
  }, result);

```



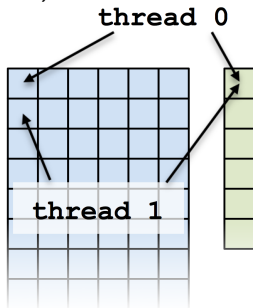
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```

Problem: What if we don't have enough rows to saturate the GPU?



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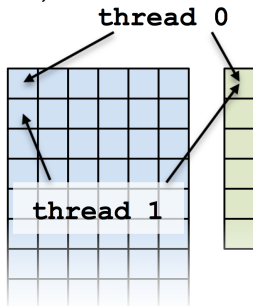
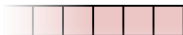
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Problem: What if we don't have enough rows to saturate the GPU?

Solutions?



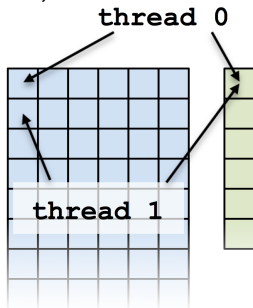
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Problem: What if we don't have enough rows to saturate the GPU?

Solutions?

- ▶ Atomics
- ▶ Thread teams

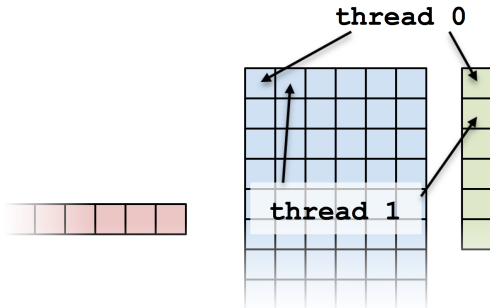


Atomics kernel:

```

Kokkos::parallel_for("yAx", N*M,
  KOKKOS_LAMBDA (const size_t index) {
    const int row = extractRow(index);
    const int col = extractCol(index);
    atomic_add(&result, y(row) * A(row,col) * x(col));
  });

```



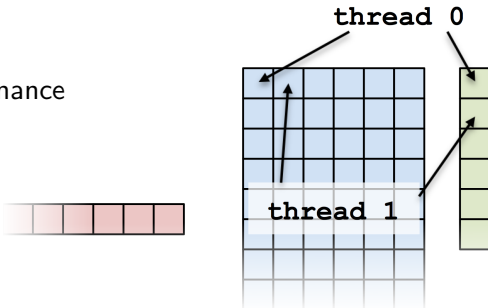
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    atomic_add(&result, y(row) * A(row,col) * x(col));
  });

```

Problem: Poor performance



Using an atomic with every element is doing scalar integration with atomics. (See module 3)

Instead, you could envision doing a large number of `parallel_reduce` kernels.

```
for each row
  Functor functor(row, ...);
  parallel_reduce(M, functor);
}
```

Using an atomic with every element is doing scalar integration with atomics. (See module 3)

Instead, you could envision doing a large number of `parallel_reduce` kernels.

```
for each row
  Functor functor(row, ...);
  parallel_reduce(M, functor);
}
```

This is an example of *hierarchical work*.

Important concept: Hierarchical parallelism

Algorithms that exhibit hierarchical structure can exploit hierarchical parallelism with **thread teams**.

Important concept: Thread team

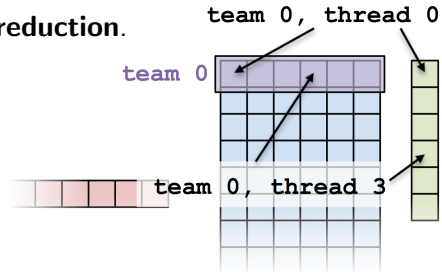
A collection of threads which are guaranteed to be executing **concurrently** and **can synchronize**.

Important concept: Thread team

A collection of threads which are guaranteed to be executing **concurrently** and **can synchronize**.

High-level **strategy**:

1. Do **one parallel launch** of N teams.
2. Each team handles a row.
3. The threads within **teams perform a reduction**.
4. The thread teams **perform a reduction**.



The final hierarchical parallel kernel:

```
parallel_reduce("yAx",
  team_policy(N, Kokkos::AUTO),

  KOKKOS_LAMBDA (const member_type & teamMember, double & update)
    int row = teamMember.league_rank();

    double thisRowsSum = 0;
    parallel_reduce(TeamThreadRange(teamMember, M),
      [=] (int col, double & innerUpdate) {
        innerUpdate += A(row, col) * x(col);
      }, thisRowsSum);

    if (teamMember.team_rank() == 0) {
      update += y(row) * thisRowsSum;
    }
  }, result);
```

Important point

Using teams is changing the execution *policy*.

“**Flat** parallelism” uses RangePolicy:

We specify a *total amount of work*.

```
// total work = N  
parallel_for("Label",  
    RangePolicy<ExecutionSpace>(0,N), functor);
```

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Using teams is changing the execution *policy*.

“**Flat** parallelism” uses RangePolicy:

We specify a *total amount of work*.

```
// total work = N
parallel_for("Label",
    RangePolicy<ExecutionSpace>(0,N), functor);
```

“**Hierarchical** parallelism” uses TeamPolicy:

We specify a *team size* and a *number of teams*.

```
// total work = numberOfTeams * teamSize
parallel_for("Label",
    TeamPolicy<ExecutionSpace>(numberOfTeams, teamSize), functor);
```


Important point

When using teams, functor operators receive a *team member*.

```
using member_type = typename TeamPolicy<ExecSpace>::member_type;

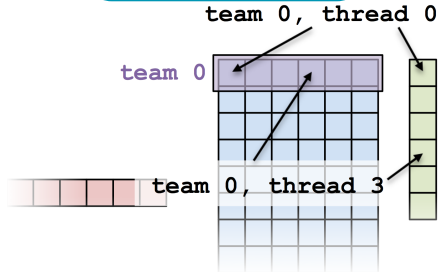
void operator()(const member_type & teamMember) {
    // How many teams are there?
    const unsigned int league_size = teamMember.league_size();

    // Which team am I on?
    const unsigned int league_rank = teamMember.league_rank();

    // How many threads are in the team?
    const unsigned int team_size = teamMember.team_size();

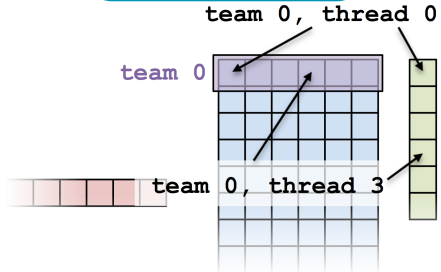
    // Which thread am I on this team?
    const unsigned int team_rank = teamMember.team_rank();

    // Make threads in a team wait on each other:
    teamMember.team_barrier();
}
```



First attempt at exercise:

```
operator() (member_type & teamMember ) {
    const size_t row = teamMember.league_rank();
    const size_t col = teamMember.team_rank();
    atomic_add(&result, y(row) * A(row, col) * x(entry));
}
```



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operator() (member_type & teamMember ) {
    const size_t row = teamMember.league_rank();
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```

- ▶ When team size \neq number of columns, how are units of work mapped to team's member threads? Is the mapping architecture-dependent?

Second attempt at exercise:

Divide row length among team members.

```
operator() (member_type & teamMember ) {  
    const size_t row = teamMember.league_rank();  
  
    int begin = teamMember.team_rank();  
    for(int col = begin; col < M; col += teamMember.team_size()) {  
        atomic_add(&result, y(row) * A(row,col) * x(entry));  
    }  
}
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    }  
}
```

- ▶ Still bad because `atomic_add` performs badly under high contention, how can team's member threads performantly cooperate for a nested reduction?
- ▶ On CPUs you get a bad data access pattern: this hardcodes coalesced access, but not caching.

We shouldn't be hard-coding the work mapping...

```
operator() (member_type & teamMember, double & update) {
    const int row = teamMember.league_rank();
    double thisRowsSum;
    'do a reduction'('over M columns',
        [=] (const int col) {
            thisRowsSum += A(row,col) * x(col);
        });
    if (teamMember.team_rank() == 0) {
        update += (row) * thisRowsSum;
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Key idea: this *is* a parallel execution.

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⇒ **Nested parallel patterns**

TeamThreadRange:

```
operator() (const member_type & teamMember, double & update ) {
    const int row = teamMember.league_rank();
    double thisRowsSum;
    parallel_reduce(TeamThreadRange(teamMember, M),
        [=] (const int col, double & thisRowsPartialSum ) {
            thisRowsPartialSum += A(row, col) * x(col);
        }, thisRowsSum );
    if (teamMember.team_rank() == 0) {
        update += y(row) * thisRowsSum;
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    if (teamMember.team_rank() == 0) {
        update += y(row) * thisRowsSum;
    }
}

```

- ▶ The **mapping** of work indices to threads is **architecture-dependent**.
- ▶ The **amount of work** given to the TeamThreadRange **need not be a multiple** of the team_size.
- ▶ Intrateam **reduction handled** by Kokkos.

Anatomy of nested parallelism:

```
parallel_outer("Label",
  TeamPolicy<ExecutionSpace>(numberOfTeams, teamSize),
  KOKKOS_LAMBDA (const member_type & teamMember[, ...]) {
    /* beginning of outer body */
    parallel_inner(
      TeamThreadRange(teamMember, thisTeamsRangeSize),
      [=] (const unsigned int indexWithinBatch[, ...]) {
        /* inner body */
      }[, ...]);
    /* end of outer body */
  }[, ...]);
```

- ▶ parallel_outer and parallel_inner may be any combination of for and/or reduce.
- ▶ The inner lambda may capture by reference, but capture-by-value is recommended.
- ▶ The policy of the inner lambda is always a TeamThreadRange.
- ▶ TeamThreadRange cannot be nested.

In practice, you can **let Kokkos decide**:

```
parallel_something(  
    TeamPolicy<ExecutionSpace>(numberOfTeams , Kokkos::AUTO),  
    /* functor */);
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GPUs

- ▶ Special hardware available for coordination within a team.
- ▶ Within a team 32 (NVIDIA) or 64 (AMD) threads execute “lock step.”
- ▶ Maximum team size: **1024**; Recommended team size: **128/256**

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Intel Xeon Phi:

- ▶ Recommended team size: # hyperthreads per core
- ▶ Hyperthreads share entire cache hierarchy
a well-coordinated team avoids cache-thrashing

Details:

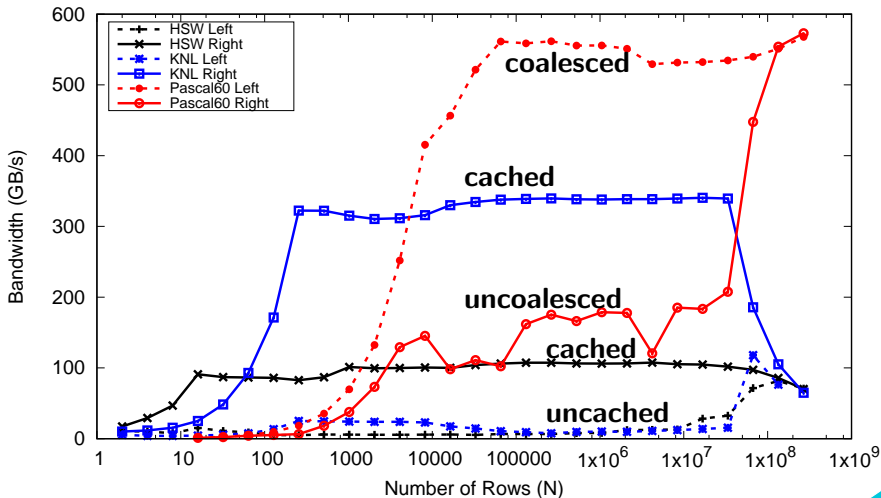
- ▶ Location: `Exercises/team_policy/`
- ▶ Replace `RangePolicy<Space>` with `TeamPolicy<Space>`
- ▶ Use `AUTO` for `team_size`
- ▶ Make the inner loop a `parallel_reduce` with `TeamThreadRange` policy
- ▶ Experiment with the combinations of `Layout`, `Space`, `N` to view performance
- ▶ Hint: what should the layout of `A` be?

Things to try:

- ▶ Vary problem size and number of rows (`-S ...; -N ...`)
- ▶ Compare behavior with Exercise 4 for very non-square matrices
- ▶ Compare behavior of CPU vs GPU

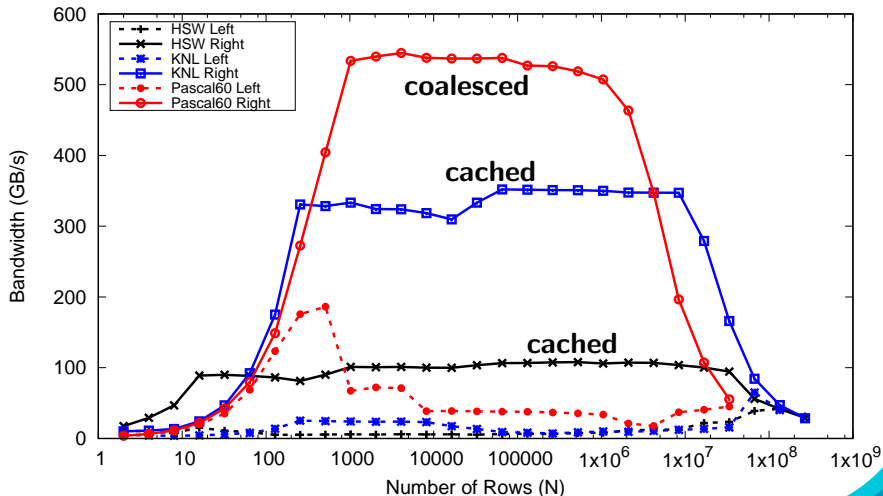
<y|Ax> Exercise 04 (Layout) Fixed Size

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<y|Ax> Exercise 05 (Layout/Teams) Fixed Size

KNL: Xeon Phi 68c HSW: Dual Xeon Haswell 2x16c Pascal60: Nvidia GPU



Exposing Vector Level Parallelism

- ▶ Optional **third level** in the hierarchy: `ThreadVectorRange`
 - ▶ Can be used for `parallel_for`, `parallel_reduce`, or `parallel_scan`.
- ▶ Maps to vectorizable loop on CPUs or (sub-)warp level parallelism on GPUs.
- ▶ Enabled with a **runtime** vector length argument to `TeamPolicy`
- ▶ There is **no** explicit access to a vector lane ID.
- ▶ Depending on the backend the full global parallel region has active vector lanes.
- ▶ `TeamVectorRange` uses both **thread** and **vector** parallelism.

Anatomy of nested parallelism:

```

parallel_outer("Label",
  TeamPolicy<>(numberOfTeams, teamSize, vectorLength),
  KOKKOS_LAMBDA (const member_type & teamMember[, ...]) {
    /* beginning of outer body */
    parallel_middle(
      TeamThreadRange(teamMember, thisTeamsRangeSize),
      [=] (const int indexWithinBatch[, ...]) {
        /* begin middle body */
        parallel_inner(
          ThreadVectorRange(teamMember, thisVectorRangeSize),
          [=] (const int indexVectorRange[, ...]) {
            /* inner body */
          }[, ...]);
        /* end middle body */
      }[, ...]);
    parallel_middle(
      TeamVectorRange(teamMember, someSize),
      [=] (const int indexTeamVector[, ...]) {
        /* nested body */
      }[, ...]);
    /* end of outer body */
  }[, ...]);

```

Question: What will the value of `totalSum` be?

```
int totalSum = 0;
parallel_reduce("Sum", RangePolicy<>(0, numberOfThreads),
  KOKKOS_LAMBDA (size_t& index, int& partialSum) {
    int thisThreadsSum = 0;
    for (int i = 0; i < 10; ++i) {
        ++thisThreadsSum;
    }
    partialSum += thisThreadsSum;
}, totalSum);
```

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```

`totalSum = numberOfThreads * 10`

Question: What will the value of `totalSum` be?

```
int totalSum = 0;
parallel_reduce("Sum", TeamPolicy<>(numberOfTeams, team_size),
    KOKKOS_LAMBDA (member_type& teamMember, int& partialSum) {
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`totalSum = numberOfTeams * team_size * 10`

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int totalSum = 0;
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    int thisTeamsSum = 0;
    parallel_reduce(TeamThreadRange(teamMember, team_size),
      [=] (const int index, int& thisTeamsPartialSum) {
        int thisThreadsSum = 0;
        for (int i = 0; i < 10; ++i) {
            ++thisThreadsSum;
        }
        thisTeamsPartialSum += thisThreadsSum;
      }, thisTeamsSum);
    partialSum += thisTeamsSum;
}, totalSum);
```

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    int thisThreadsSum = 0;
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      ++thisThreadsSum;
    }
    thisTeamsPartialSum += thisThreadsSum;
  }, thisTeamsSum);
  partialSum += thisTeamsSum;
}, totalSum);
```

totalSum = numberOfTeams * team_size * team_size * 10

The single pattern can be used to restrict execution

- ▶ Like parallel patterns it takes a policy, a lambda, and optionally a broadcast argument.
- ▶ Two policies: PerTeam and PerThread.
- ▶ Equivalent to OpenMP **single** directive with **nowait**

```
// Restrict to once per thread
single(PerThread(teamMember), [&] () {
    // code
});
```

```
// Restrict to once per team with broadcast
int broadcastedValue = 0;
single(PerTeam(teamMember), [&] (int& broadcastedValue_local) {
    broadcastedValue_local = special value assigned by one;
}, broadcastedValue);
// Now everyone has the special value
```

The previous example was extended with an outer loop over “Elements” to expose a third natural layer of parallelism.

Details:

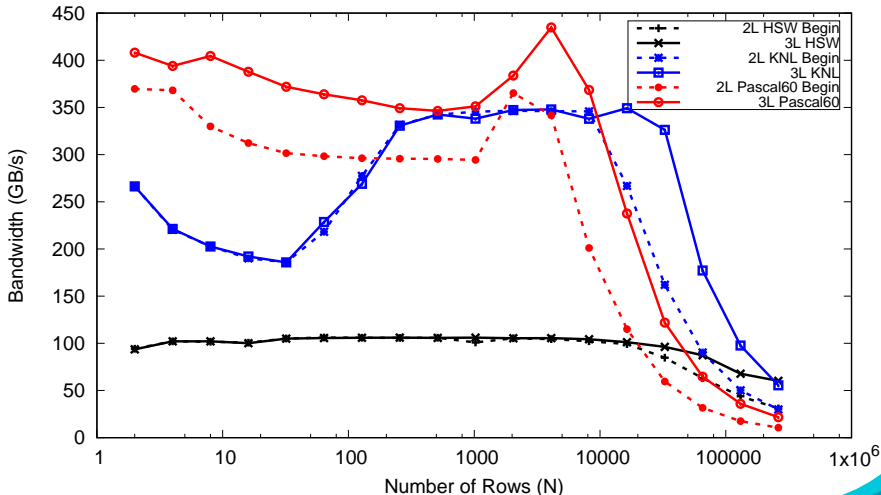
- ▶ Location: `Exercises/team_vector_loop/`
- ▶ Use the `single` policy instead of checking team rank
- ▶ Parallelize all three loop levels.

Things to try:

- ▶ Vary problem size and number of rows (`-S ...; -N ...`)
- ▶ Compare behavior with `TeamPolicy` Exercise for very non-square matrices
- ▶ Compare behavior of CPU vs GPU

<y|Ax> Exercise 06 (Three Level Parallelism) Fixed Size

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- ▶ **Hierarchical work** can be parallelized via hierarchical parallelism.
- ▶ Hierarchical parallelism is leveraged using **thread teams** launched with a `TeamPolicy`.
- ▶ Team “worksets” are processed by a team in nested `parallel_for` (or `reduce` or `scan`) calls with a `TeamThreadRange`, `ThreadVectorRange`, and `TeamVectorRange` policy.
- ▶ Execution can be restricted to a subset of the team with the `single` pattern using either a `PerTeam` or `PerThread` policy.

Scratch memory

Learning objectives:

- ▶ Understand concept of **team** and **thread** private **scratch pads**
- ▶ Understand how scratch memory can **reduce global memory accesses**
- ▶ Recognize **when to use** scratch memory
- ▶ Understand **how to use** scratch memory and when barriers are necessary

Two Levels of Scratch Space

- ▶ Level 0 is limited in size but fast.
- ▶ Level 1 allows larger allocations but is equivalent to High Bandwidth Memory in latency and bandwidth.

Team or Thread private memory

- ▶ Typically used for per work-item temporary storage.
- ▶ Advantage over pre-allocated memory is aggregate size scales with number of threads, not number of work-items.

Manually Managed Cache

- ▶ Explicitly cache frequently used data.
- ▶ Exposes hardware specific on-core scratch space (e.g. NVIDIA GPU Shared Memory).

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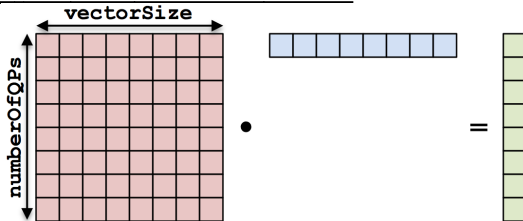
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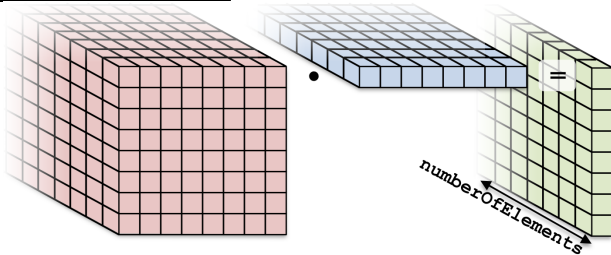
- ▶ Explicitly cache frequently used data.
- ▶ Exposes hardware specific on-core scratch space (e.g. NVIDIA GPU Shared Memory).

Now: Discuss Manually Managed Cache Usecase.

One slice of contractDataFieldScalar:



```
for (qp = 0; qp < numberOfQPs; ++qp) {  
    total = 0;  
    for (i = 0; i < vectorSize; ++i) {  
        total += A(qp, i) * B(i);  
    }  
    result(qp) = total;  
}
```

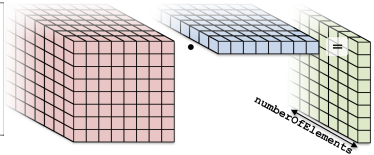
contractDataFieldScalar:

```

for (element = 0; element < numberOfElements; ++element) {
  for (qp = 0; qp < numberOfQPs; ++qp) {
    total = 0;
    for (i = 0; i < vectorSize; ++i) {
      total += A(element, qp, i) * B(element, i);
    }
    result(element, qp) = total;
  }
}

```

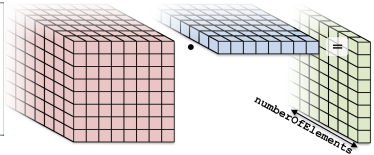
```
for (element = 0; element < numberOfElements; ++element) {  
  for (qp = 0; qp < numberOfQPs; ++qp) {  
    total = 0;  
    for (i = 0; i < vectorSize; ++i) {  
      total += A(element, qp, i) * B(element, i);  
    }  
    result(element, qp) = total;  
  }  
}
```



Parallelization approaches:

- ▶ Each thread handles an element.
Threads: numberOfElements

```
for (element = 0; element < numberOfElements; ++element) {  
  for (qp = 0; qp < numberOfQPs; ++qp) {  
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      total += A(element, qp, i) * B(element, i);  
    }  
    result(element, qp) = total;  
  }  
}
```



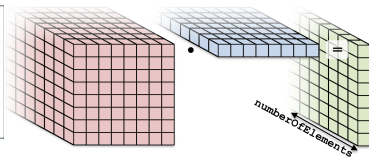
Parallelization approaches:

- ▶ Each thread handles an element.
Threads: `numberOfElements`
- ▶ Each thread handles a qp.
Threads: `numberOfElements * numberOfQPs`

```

for (element = 0; element < numberOfElements; ++element) {
  for (qp = 0; qp < numberOfQPs; ++qp) {
    total = 0;
    for (i = 0; i < vectorSize; ++i) {
      total += A(element, qp, i) * B(element, i);
    }
    result(element, qp) = total;
  }
}

```



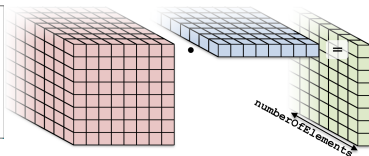
Parallelization approaches:

- ▶ Each thread handles an element.
Threads: numberOfElements
- ▶ Each thread handles a qp.
Threads: numberOfElements * numberOfQPs
- ▶ Each thread handles an i.
Threads: numElements * numQPs * vectorSize
Requires a parallel_reduce.

```

for (element = 0; element < numberOfElements; ++element) {
  for (qp = 0; qp < numberOfQPs; ++qp) {
    total = 0;
    for (i = 0; i < vectorSize; ++i) {
      total += A(element, qp, i) * B(element, i);
    }
    result(element, qp) = total;
  }
}

```



Parallelization approaches:

- ▶ Each thread handles an element.

Threads: numberOfElements

- ▶ Each thread handles a qp.

Threads: numberOfElements * numberOfQPs

- ▶ Each thread handles an i.

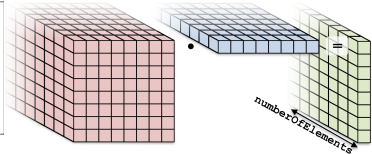
Threads: numElements * numQPs * vectorSize

Requires a parallel_reduce.

```

for (element = 0; element < numberOfElements; ++element) {
  for (qp = 0; qp < numberOfQPs; ++qp) {
    total = 0;
    for (i = 0; i < vectorSize; ++i) {
      total += A(element, qp, i) * B(element, i);
    }
    result(element, qp) = total;
  }
}

```



Flat kernel: Each thread handles a quadrature point

```

parallel_for("L", MDRangePolicy<Rank<2>>({0,0},{numE,numQP}),
  KOKKOS_LAMBDA(int element, int qp) {
    double total = 0;
    for (int i = 0; i < vectorSize; ++i) {
      total += A(element, qp, i) * B(element, i);
    }
    result(element, qp) = total;
  }
}

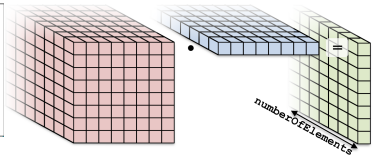
```



```

for (element = 0; element < numberOfElements; ++element) {
  for (qp = 0; qp < numberOfQPs; ++qp) {
    total = 0;
    for (i = 0; i < vectorSize; ++i) {
      total += A(element, qp, i) * B(element, i);
    }
    result(element, qp) = total;
  }
}

```



Teams kernel: Each team handles an element

```

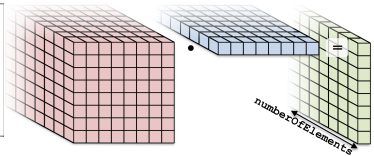
operator()(member_type teamMember) {
  int element = teamMember.league_rank();
  parallel_for(
    TeamThreadRange(teamMember, numberOfQPs),
    [=] (int qp) {
      double total = 0;
      for (int i = 0; i < vectorSize; ++i) {
        total += A(element, qp, i) * B(element, i);
      }
      result(element, qp) = total;
    });
}

```

```

for (element = 0; element < numberOfElements; ++element) {
  for (qp = 0; qp < numberOfQPs; ++qp) {
    total = 0;
    for (i = 0; i < vectorSize; ++i) {
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    }
    result(element, qp) = total;
  }
}

```



Teams kernel: Each team handles an element

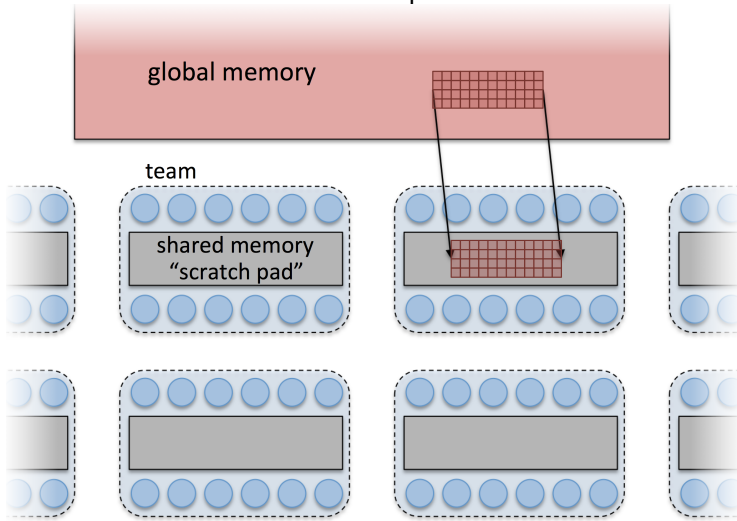
```

operator()(member_type teamMember) {
  int element = teamMember.league_rank();
  parallel_for(
    TeamThreadRange(teamMember, numberOfQPs),
    [=] (int qp) {
      double total = 0;
      for (int i = 0; i < vectorSize; ++i) {
        total += A(element, qp, i) * B(element, i);
      }
      result(element, qp) = total;
    });
}

```

No real advantage (yet)

Each team has access to a “scratch pad”.



Scratch memory (scratch pad) as manual cache:

- ▶ Accessing data in (level 0) scratch memory is (usually) **much faster** than global memory.
- ▶ **GPUs** have separate, dedicated, small, low-latency scratch memories (*NOT subject to coalescing requirements*).
- ▶ **CPUs** don't have special hardware, but programming with scratch memory results in cache-aware memory access patterns.
- ▶ Roughly, it's like a *user-managed* L1 cache.

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- ▶ Roughly, it's like a *user-managed* L1 cache.

Important concept

When members of a team read the same data multiple times, it's better to load the data into scratch memory and read from there.

Scratch memory for temporary per work-item storage:

- ▶ Scenario: Algorithm requires temporary workspace of size W .
- ▶ **Without scratch memory:** pre-allocate space for N work-items of size $N \times W$.
- ▶ **With scratch memory:** Kokkos pre-allocates space for each Team or Thread of size $T \times W$.
- ▶ `PerThread` and `PerTeam` scratch can be used concurrently.
- ▶ Level 0 and Level 1 scratch memory can be used concurrently.

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- ▶ `PerThread` and `PerTeam` scratch can be used concurrently.
- ▶ Level 0 and Level 1 scratch memory can be used concurrently.

Important concept

If an algorithm requires temporary workspace for each work-item, then use Kokkos' scratch memory.

To use scratch memory, you need to:

1. **Tell Kokkos how much** scratch memory you'll need.
2. **Make** scratch memory **views** inside your kernels.

To use scratch memory, you need to:

1. **Tell Kokkos how much** scratch memory you'll need.
2. **Make** scratch memory **views** inside your kernels.

```
TeamPolicy<ExecutionSpace> policy(numberOfTeams, teamSize);

// Define a scratch memory view type
using ScratchPadView =
    View<double*, ExecutionSpace::scratch_memory_space>;
// Compute how much scratch memory (in bytes) is needed
size_t bytes = ScratchPadView::shmem_size(vectorSize);

// Tell the policy how much scratch memory is needed
int level = 0;
parallel_for(policy.set_scratch_size(level, PerTeam(bytes)),
    KOKKOS_LAMBDA (const member_type& teamMember) {

    // Create a view from the pre-existing scratch memory
    ScratchPadView scratch(teamMember.team_scratch(level),
        vectorSize);

});
```

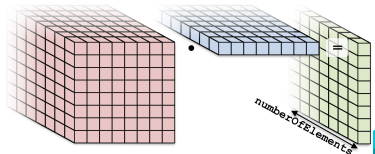
Kernel outline for teams with scratch memory:

```

operator()(member_type teamMember) {
    ScratchPadView scratch(teamMember.team_scratch(0),
                           vectorSize);
    // TODO: load slice of B into scratch

    parallel_for(
        TeamThreadRange(teamMember, numberOfQPs),
        [=] (int qp) {
            double total = 0;
            for (int i = 0; i < vectorSize; ++i) {
                // total += A(element, qp, i) * B(element, i);
                total += A(element, qp, i) * scratch(i);
            }
            result(element, qp) = total;
        });
}

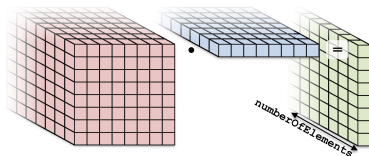
```



How to populate the scratch memory?

- ▶ One thread loads it all?

```
if (teamMember.team_rank() == 0) {  
    for (int i = 0; i < vectorSize; ++i) {  
        scratch(i) = B(element, i);  
    }  
}
```



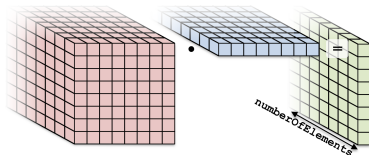
How to populate the scratch memory?

- ▶ ~~One thread loads it all?~~ **Serial**

```
if (teamMember.team_rank() == 0) {
  for (int i = 0; i < vectorSize; ++i) {
    scratch(i) = B(element, i);
  }
}
```

- ▶ Each thread loads one entry?

```
scratch(team_rank) = B(element, team_rank);
```



How to populate the scratch memory?

- ▶ ~~One thread loads it all?~~ **Serial**

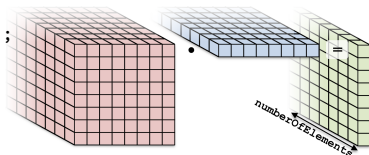
```
if (teamMember.team_rank() == 0) {
  for (int i = 0; i < vectorSize; ++i) {
    scratch(i) = B(element, i);
  }
}
```

- ▶ ~~Each thread loads one entry?~~ **teamSize \neq vectorSize**

```
scratch(team_rank) = B(element, team_rank);
```

- ▶ TeamVectorRange

```
parallel_for(
  TeamVectorRange(teamMember, vectorSize),
  [=] (int i) {
    scratch(i) = B(element, i);
  });
```



How to populate the scratch memory?

- ▶ ~~One thread loads it all?~~ **Serial**

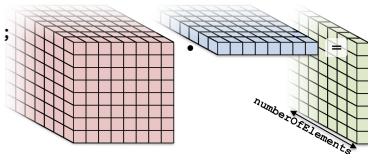
```
if (teamMember.team_rank() == 0) {
  for (int i = 0; i < vectorSize; ++i) {
    scratch(i) = B(element, i);
  }
}
```

- ▶ ~~Each thread loads one entry?~~ **teamSize \neq vectorSize**

```
scratch(team_rank) = B(element, team_rank);
```

- ▶ **TeamVectorRange**

```
parallel_for(
  TeamVectorRange(teamMember, vectorSize),
  [=] (int i) {
    scratch(i) = B(element, i);
  });
```



(incomplete) Kernel for teams with scratch memory:

```
operator()(member_type teamMember) {
    ScratchPadView scratch(...);

    parallel_for(TeamVectorRange(teamMember, vectorSize),
        [=] (int i) {
            scratch(i) = B(element, i);
        });
    // TODO: fix a problem at this location

    parallel_for(TeamThreadRange(teamMember, numberOfQPs),
        [=] (int qp) {
            double total = 0;
            for (int i = 0; i < vectorSize; ++i) {
                total += A(element, qp, i) * scratch(i);
            }
            result(element, qp) = total;
        });
}
```

(incomplete) Kernel for teams with scratch memory:

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operator()(member_type teamMember) {
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        });
    // TODO: fix a problem at this location

    parallel_for(TeamThreadRange(teamMember, numberOfQPs),
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            double total = 0;
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                total += A(element, qp, i) * scratch(i);
            }
            result(element, qp) = total;
        });
}
```

Problem: threads may start to use `scratch` before all threads are done loading.

Kernel for teams with scratch memory:

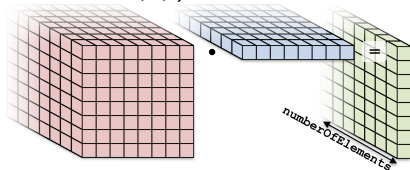
```

operator()(member_type teamMember) {
    ScratchPadView scratch(...);

    parallel_for(ThreadVectorRange(teamMember, vectorSize),
        [=] (int i) {
            scratch(i) = B(element, i);
        });
    teamMember.team_barrier();

    parallel_for(TeamThreadRange(teamMember, numberOfQPs),
        [=] (int qp) {
            double total = 0;
            for (int i = 0; i < vectorSize; ++i) {
                total += A(element, qp, i) * scratch(i);
            }
            result(element, qp) = total;
        });
}

```



Use Scratch Memory to explicitly cache the x-vector for each element.

Details:

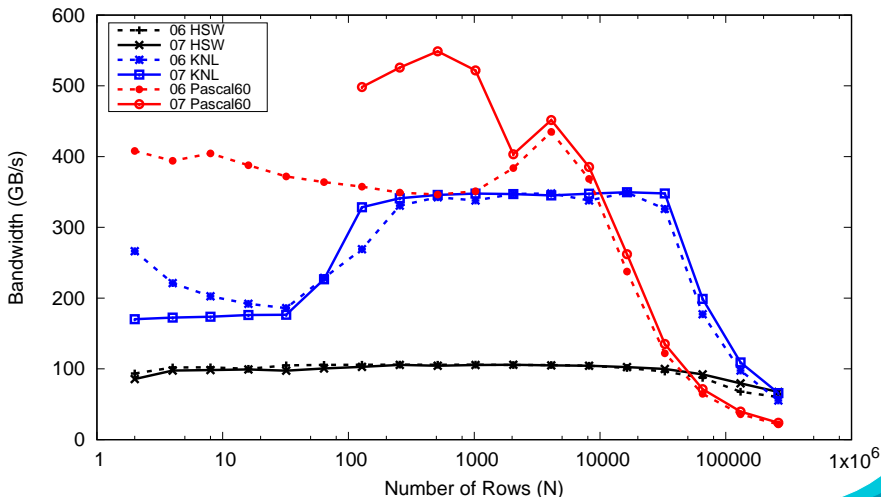
- ▶ Location: `Exercises/team_scratch_memory/`
- ▶ Create a scratch view
- ▶ Fill the scratch view in parallel using a `TeamVectorRange`

Things to try:

- ▶ Vary problem size and number of rows (`-S ...; -N ...`)
- ▶ Compare behavior with Exercise 6
- ▶ Compare behavior of CPU vs GPU

Exercise 07 (Scratch Memory) Fixed Size

KNL: Xeon Phi 68c HSW: Dual Xeon Haswell 2x16c Pascal60: Nvidia GPU



Allocating scratch in different levels:

```
int level = 1; // valid values 0,1  
policy.set_scratch_size(level, PerTeam(bytes));
```

Allocating scratch in different levels:

```
int level = 1; // valid values 0,1
policy.set_scratch_size(level, PerTeam(bytes));
```

Using PerThread, PerTeam or both:

```
policy.set_scratch_size(level, PerTeam(bytes));
policy.set_scratch_size(level, PerThread(bytes));
policy.set_scratch_size(level, PerTeam(bytes1),
                        PerThread(bytes2));
```

Allocating scratch in different levels:

```
int level = 1; // valid values 0,1
policy.set_scratch_size(level, PerTeam(bytes));
```

Using PerThread, PerTeam or both:

```
policy.set_scratch_size(level, PerTeam(bytes));
policy.set_scratch_size(level, PerThread(bytes));
policy.set_scratch_size(level, PerTeam(bytes1),
                        PerThread(bytes2));
```

Using both levels of scratch:

```
policy.set_scratch_size(0, PerTeam(bytes0))
    .set_scratch_size(1, PerThread(bytes1));
```

- ▶ **Scratch Memory** can be use with the TeamPolicy to provide thread or team **private** memory.
- ▶ Usecase: per work-item temporary storage or manual caching.
- ▶ Scratch memory exposes on-chip user managed caches (e.g. on NVIDIA GPUs)
- ▶ The size must be determined before launching a kernel.
- ▶ Two levels are available: large/slow and small/fast.

Unique Token

Learning objectives:

- ▶ Understand concept of unique tokens and thread-safe resource access.
- ▶ Learn how to acquire per-team unique ids.
- ▶ Understand the difference between **Global** and **Instance** scope.

Why do we need a unique token concept?

- ▶ Within Functor operator / Lambda there is no portable way to identify the active execution resource (thread id)
- ▶ Some algorithms make efficient use of shared resources by dividing based on execution resource (thread id)
- ▶ Thread Id is not consistent or portable across all execution environments
- ▶ Unique Token provides consistent identifier for resource allocations and work division

Original Example: Random Number Generator Pool

```
int N = 10000000
int K = ...;
RandomGenPool pool(K,seed);
parallel_for("Loop", N, KOKKOS_LAMBDA(int i) {
    int gen_id = ...
    auto gen = pool[gen_id];
});
```

How many generators do we need (K)?

Original Example: Random Number Generator Pool

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How to get a unique one in the loop (gen_id)?

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});
```

How many generators do we need (K)?

How to get a unique one in the loop (gen_id)?

In OpenMP we could use the **thread-id** but what in CUDA?

Motivating Example

OpenMP

```
int K = omp_get_max_threads();
Kokkos::parallel_for("L", N, KOKKOS_LAMBDA(int i) {
    int tid = omp_get_thread_num();
});
```

CUDA

```
int K = N; // ??
Kokkos::parallel_for("L", N, KOKKOS_LAMBDA(int i) {
    int tid = threadIdx.x + blockDim.x * blockIdx.x; //i??
});
```

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Problem: In **CUDA** there is no way to get **hardware thread-id**.

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OpenMP

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});
```

Problem: In **CUDA** there is no way to get **hardware thread-id**.

Solution: We need a thread-safe and portable way to obtain unique identifier that is per-thread specific.

⇒ **UniqueToken**

UniqueToken is a pool of IDs

- ▶ User acquires an ID and releases it again.

```
UniqueToken<ExecutionSpace> token;
int number_of_unique_ids = token.size();
RandomGenPool pool(number_of_unique_ids, seed);
parallel_for("L", N, KOKKOS_LAMBDA(int i) {
    int id = token.acquire();
    RandomGen gen = pool(id);
    ...
    token.release(id);
});
```


UniqueToken is a pool of IDs

- ▶ User acquires an ID and releases it again.

```
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int number_of_unique_ids = token.size();  
RandomGenPool pool(number_of_unique_ids, seed);  
parallel_for("L", N, KOKKOS_LAMBDA(int i) {  
    int id = token.acquire();  
    RandomGen gen = pool(id);  
    ...  
    token.release(id);  
});
```

- ▶ Do not acquire more than one token in an iteration.
- ▶ You must release the token again.
- ▶ By default the range of ids is 0 to `ExecSpace().concurrency()`.

Sometimes you need a **Global UniqueToken**

- ▶ Submitting concurrent kernels to CUDA streams
- ▶ Shared resource in a multi-threaded environment like Legion

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UniqueToken has a Scope template parameter which by default is 'Instance' but can be 'Global'.

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- ▶ Submitting concurrent kernels to CUDA streams
- ▶ Shared resource in a multi-threaded environment like Legion

UniqueToken is Scoped

UniqueToken has a Scope template parameter which by default is 'Instance' but can be 'Global'.

```
void foo() {
    UniqueToken<ExecSpace, UniqueTokenScope::Global> token_foo;
    parallel_for("L", RangePolicy<ExecSpace>(stream1, 0, N)
        , functor_a(token_foo));
}
void bar() {
    UniqueToken<ExecSpace, UniqueTokenScope::Global> token_bar;
    parallel_for("L", RangePolicy<ExecSpace>(stream2, 0, N)
        , functor_b(token_bar));
}
```

Sometimes you need a **Global UniqueToken**

- ▶ Submitting concurrent kernels to CUDA streams
- ▶ Shared resource in a multi-threaded environment like Legion

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    parallel_for("L", RangePolicy<ExecSpace>(stream1, 0, N)
        , functor_a(token_foo));
}
void bar() {
    UniqueToken<ExecSpace, UniqueTokenScope::Global> token_bar;
    parallel_for("L", RangePolicy<ExecSpace>(stream2, 0, N)
        , functor_b(token_bar));
}
```

`token_foo` and `token_bar` will provide non-conflicting ids.

UniqueToken can also be used for Per-Team resources

There are less teams active than threads. How to get an ID?

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Sized UniqueToken

UniqueToken supports custom ranges of ids via constructing sized tokens.

Acquiring a per-team unique id requires three steps:

- ▶ Compute the range via concurrency and `team_size`.
- ▶ Create a sized UniqueToken.
 - ▶ For performance reason make it a bit larger than necessary.
- ▶ Acquire and broadcast a token in a `single` pattern.


```
// Figure out the team size
int team_size = ...;
// How many teams are actually in-flight
int num_active_teams = ExecSpace().concurrency()/team_size;
// Create the token
UniqueToken<ExecSpace> token(num_active_teams * 1.2);

parallel_for("L", TeamPolicy<ExecSpace>(N,team_size),
  KOKKOS_LAMBDA(const team_t& team) {
    int id;
    // Acquire an id and broadcast it with a single thread
    single(PerTeam(team), [&](int &lid) {
        lid = token.acquire();
    }, id);
    ...
    // Release the id again (likely you want a barrier first!)
    single(PerTeam(team), [&]() {
        token.release(id);
    });
});
```

- ▶ Location: Exercises/unique_token/Begin/
- ▶ Assignment: Convert scatter_add_loop to use UniqueToken, removing #ifdef's
- ▶ Compile and run on both CPU and GPU

```
make -j KOKKOS_DEVICES=OpenMP # CPU-only using OpenMP
make -j KOKKOS_DEVICES=Cuda   # GPU - note UVM in Makefile
# Run exercise
./uniquetoken.host
./uniquetoken.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

- ▶ **UniqueToken** provides a thread safe portable way to divide thread or team specific resources
- ▶ **UniqueToken** can be sized, such that it returns only ids within a specific range.
- ▶ A **Global** scope UniqueToken can be acquired, allowing safe ids across disjoint concurrent code sections.

Hierarchal Parallelism

- ▶ **Hierarchical work** can be parallelized via hierarchical parallelism.
- ▶ Hierarchical parallelism is leveraged using **thread teams** launched with a TeamPolicy.
- ▶ Team “worksets” are processed by a team in nested `parallel_for` (or `reduce` or `scan`) calls with a `TeamThreadRange` and `ThreadVectorRange` policy.
- ▶ Execution can be restricted to a subset of the team with the `single` pattern using either a `PerTeam` or `PerThread` policy.
- ▶ Teams can be used to **reduce contention** for global resources even in “flat” algorithms.

Scratch Space

- ▶ **Scratch Memory** can be use with the TeamPolicy to provide thread or team **private** memory.
- ▶ Usecase: per work-item temporary storage or manual caching.
- ▶ Scratch memory exposes on-chip user managed caches (e.g. on NVIDIA GPUs)
- ▶ The size must be determined before launching a kernel.
- ▶ Two levels are available: large/slow and small/fast.

Unique Token

- ▶ **UniqueToken** give a thread safe portable way to divide thread specific resources
- ▶ **UniqueToken** can be sized to restrict ids to a range.
- ▶ A **Global** UniqueToken is available.