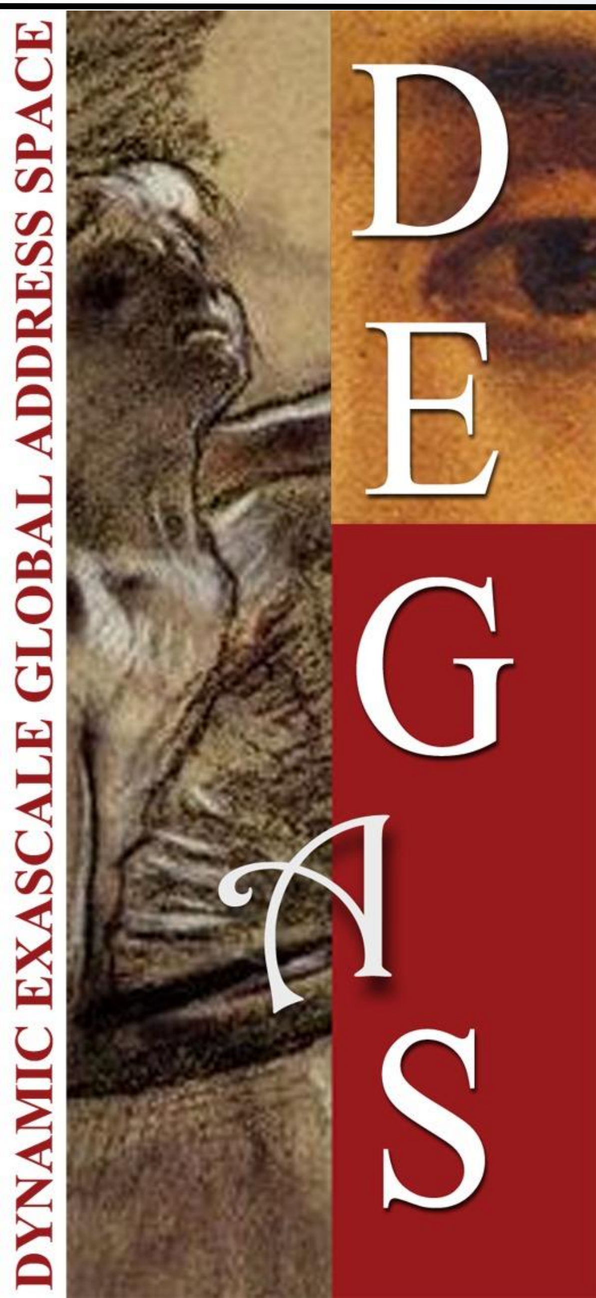

Managing Hierarchy with Teams in the SPMD Programming Model

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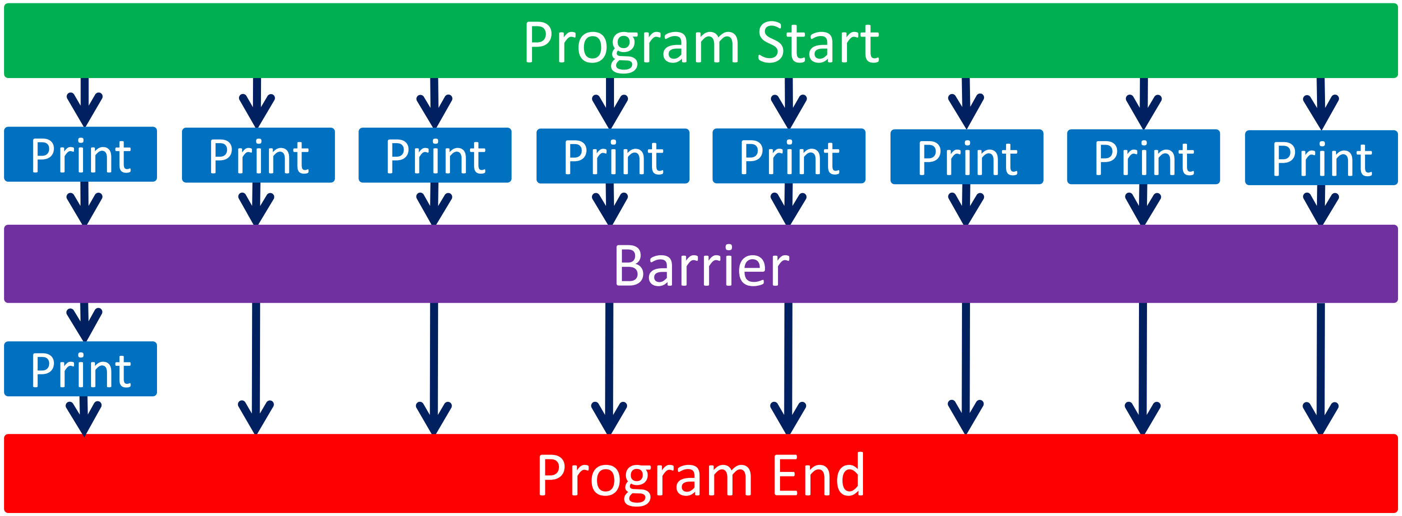
Single Program, Multiple Data Model

- The *single program, multiple data (SPMD)* execution model is the dominant programming model at scale
  - A fixed set of threads execute the same program
  - Synchronization and communication primarily through *collective* operations

```
public static void main(String[] args) {
  System.out.println("Hello from " + Ti.thisProc());
  Ti.barrier();
  if (Ti.thisProc() == 0) System.out.println("Done.");
}
```



Thread Teams

- Thread *teams* are basic units of cooperation
  - Groups of threads that cooperatively execute code
  - Collective operations over teams

- Flat teams provided by MPI, GASNet

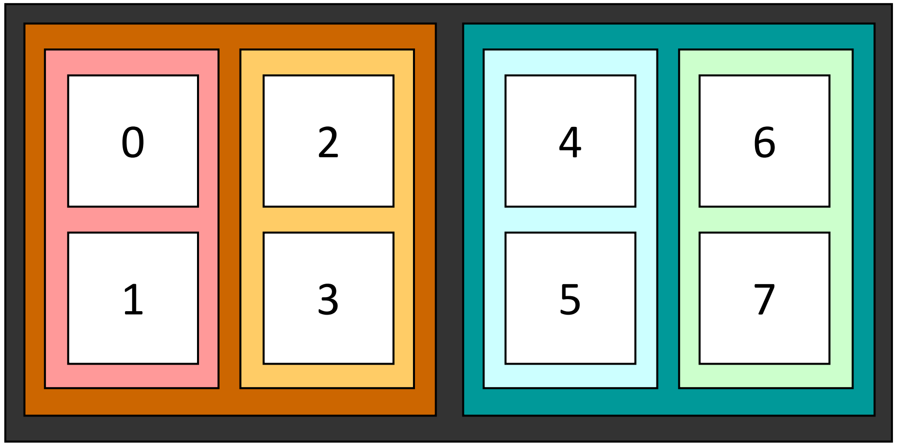
- Hierarchical teams used in Titanium, UPC++, HCAF, DASH
  - Expressive: match structure of algorithms, machines
  - Safe: eliminate many sources of deadlock
  - Composable: enable clean composition of multiple algorithms or tasks
  - Efficient: allow users to take advantage of machine structure, resulting in performance gains

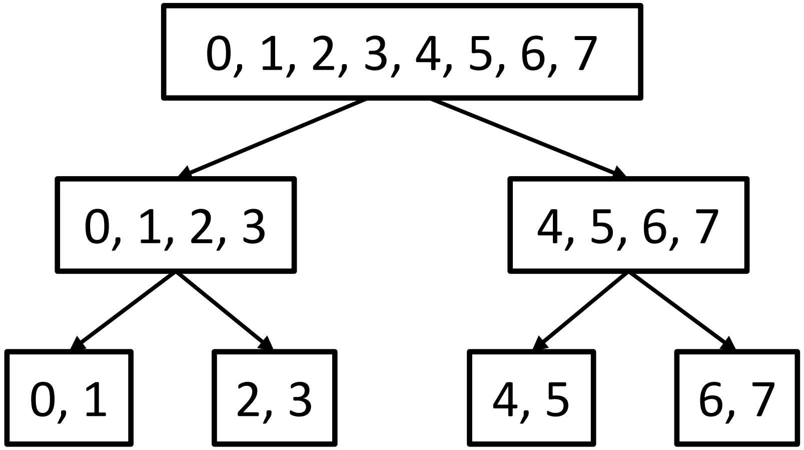
Team Data Structure

- Teams represented as tree structure
- Team structure can be created manually or automatically based on machine hierarchy

```
Team T = Ti.defaultTeam();
```

- Unbalanced structures can be created manually



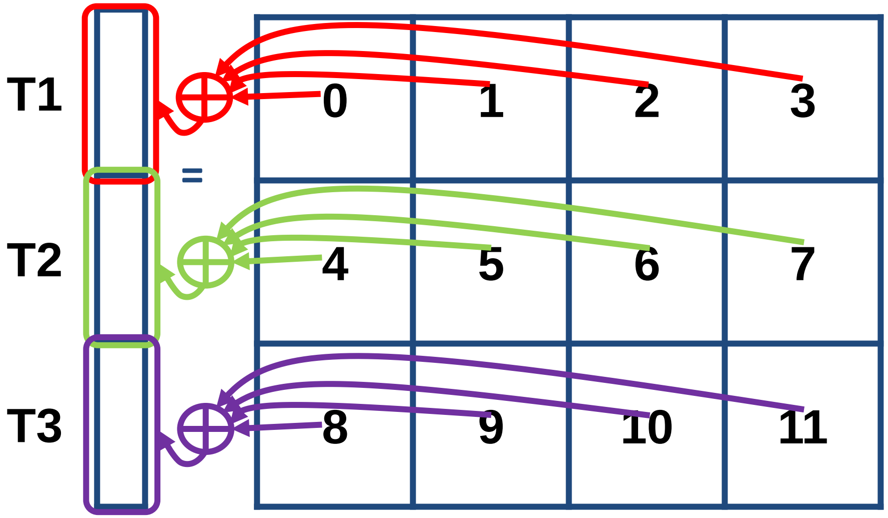


Team-Usage Constructs

- Syntactic constructs specify dynamic scope of teams

```
teamsplit(rowTeam) {
  Reduce.add(mtmp, myResults0, rpivot);
}
```

  - Collectives and queries such as **`Ti.thisProc()`** are with respect to currently scoped team
- Constructs can be nested, and recursion can be used to dynamically handle team hierarchy of arbitrary depth



Example: Sorting

- Titanium distributed sorting application using new hierarchical constructs

- Three pieces: sequential, shared memory, and distributed
  - Sequential quick sort from Java 1.4 library
  - Shared memory merge sort
    - Hierarchical teams used to express recursive algorithm
  - Distributed memory sample sort
    - Teams used to optimize communication and to compose with shared-memory sort

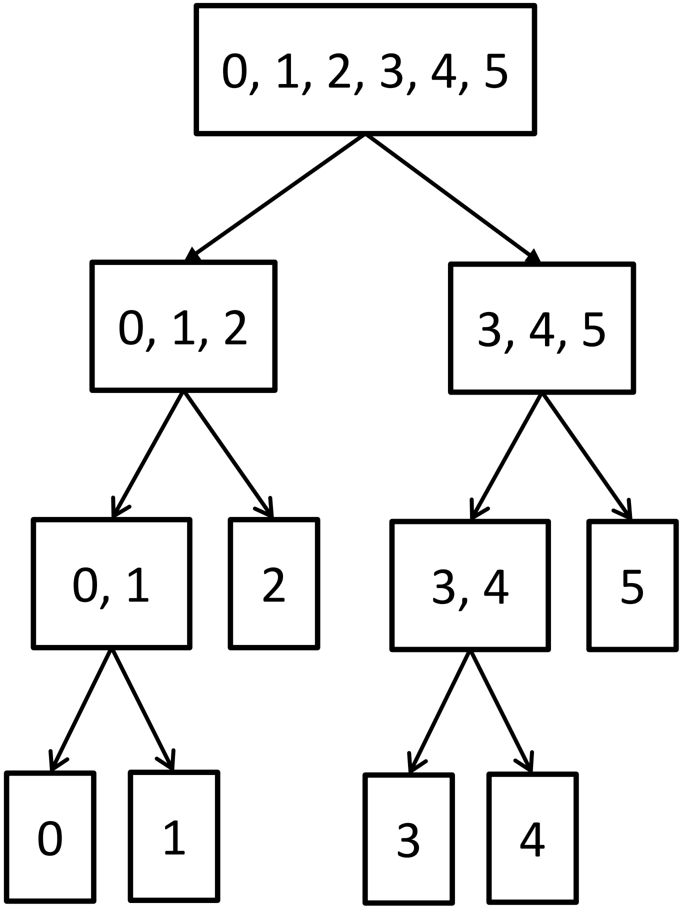
- Goal: better performance than flat sample sorting, which assumes no threads share memory

Shared-Memory Team Hierarchy

- Team hierarchy for shared-memory part of computation is binary tree

- Trivial construction

```
static void divideTeam(Team t) {
  if (t.size() > 1) {
    t.splitTeam(2);
    divideTeam(t.child(0));
    divideTeam(t.child(1));
  }
}
```



- Threads walk down to bottom of hierarchy, sort, then walk back up, merging along the way

Shared-Memory Computational Logic

- Control logic for sorting and merging

```
static void sortAndMerge(Team t) {
  if (Ti.numProcs() == 1) {
    allRes[myProc] = sequentialSort(myData);
  } else {
    teamsplit(t) {
      sortAndMerge(t.myChildTeam());
    }
    Ti.barrier();
    if (Ti.thisProc() == 0) {
      int otherProc = myProc + t.child(0).size();
      int[1d] myRes = allRes[myProc];
      int[1d] otherRes = allRes[otherProc];
      int[1d] newRes = target(t.depth(), myRes,
                              otherRes);
      allRes[myProc] = merge(myRes, otherRes, newRes);
    }
  }
}
```

Sort at bottom

Walk down team hierarchy

Walk up, merging along the way

Distributed-Memory Logic

- Flat distributed code

```
static void flatSort() {
  myData = sampleAndDistribute(myData, Ti.thisProc());
  sequentialSort(myData);
}
```

- Hierarchical distributed code

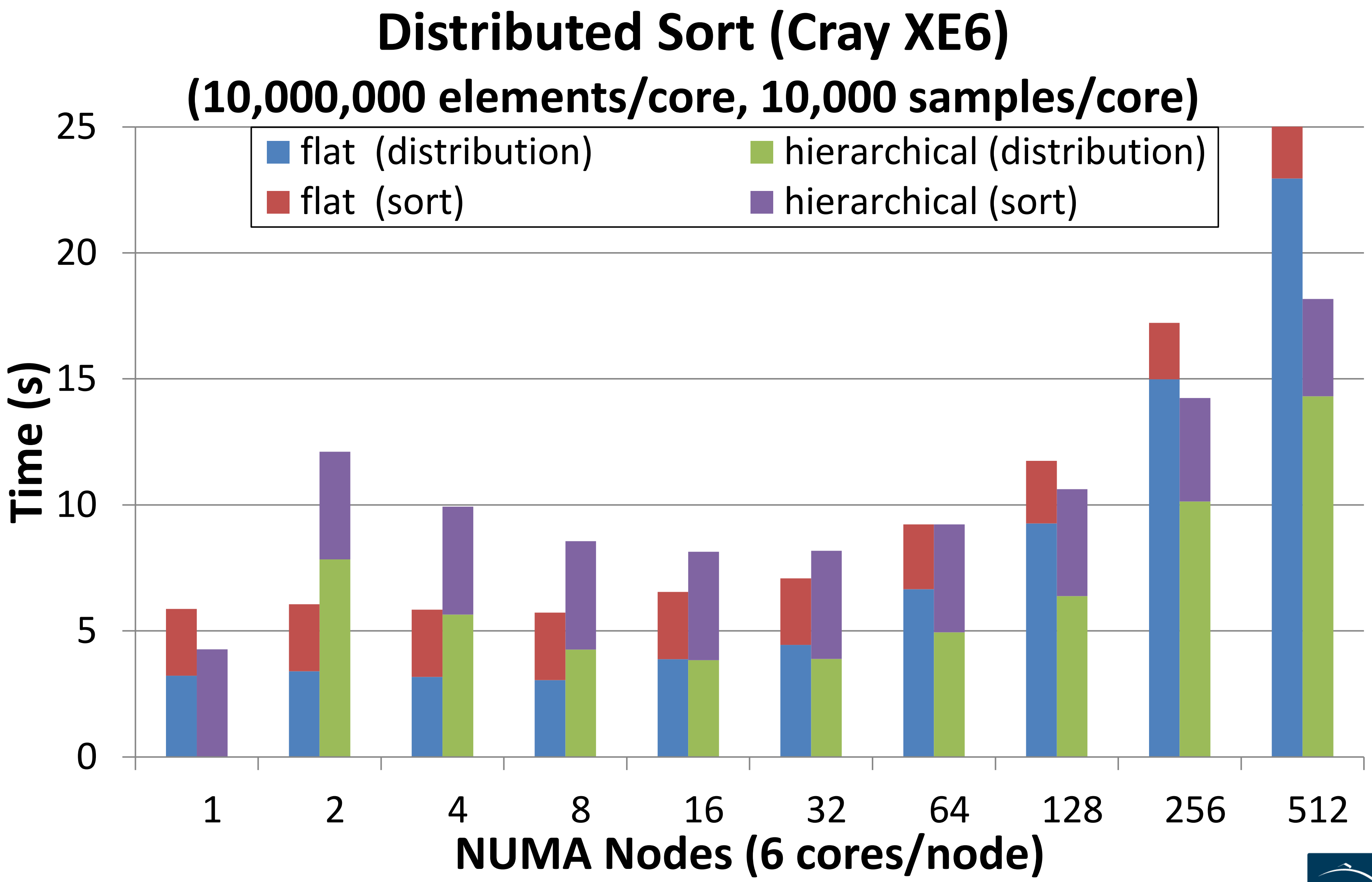
```
static void hierarchicalSort() {
  Team team = Ti.defaultTeam();
  myData = sampleAndDistribute(myData, team);
  teamsplit(t) {
    sharedMemorySort(myData);
  }
}
```

Split into shared-memory domains

Parallelize and aggregate communication between shared-memory domains

Shared-memory sort within shared-memory domains

Performance of Flat vs. Hierarchical Sort

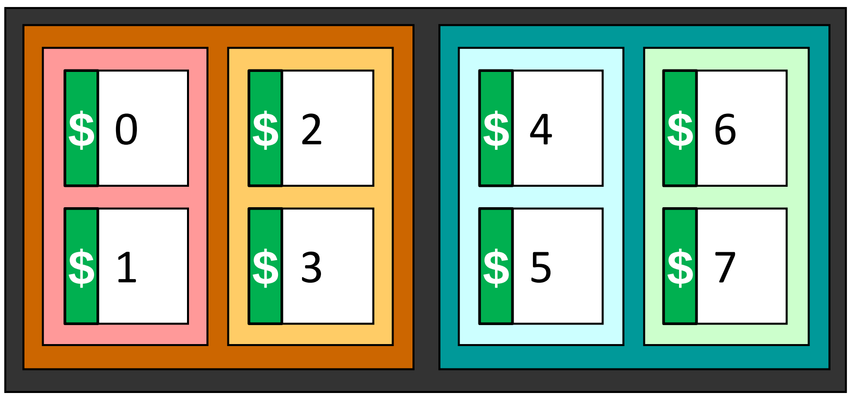


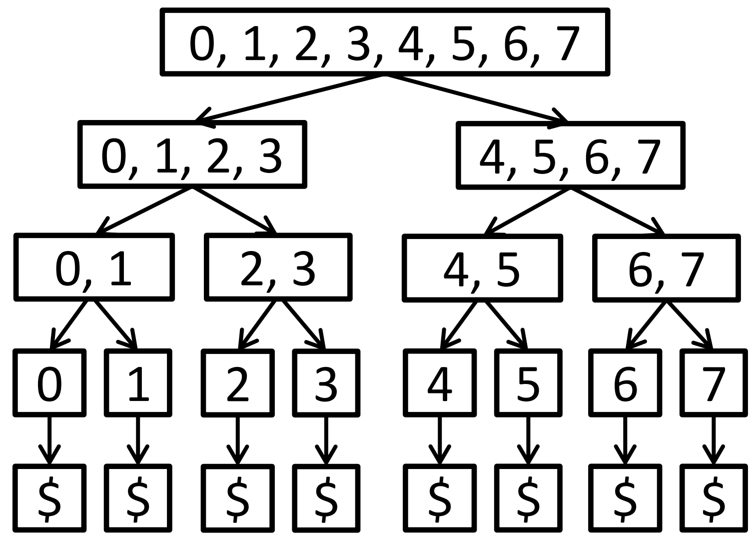
Limitations of Hierarchical Teams

- Hierarchical teams have proven to be very effective in structuring execution in SPMD programs
  - Represent logical view of execution
  - Can be synthesized from physical structure of *execution* resources
- However, they are not sufficient to represent the structure of data
  - Data are located at specific *memory* locations in a machine
  - Not necessarily one-to-one mapping between execution and memory units
- Need combination of physical memory structure (where data should be located) and logical execution structure (how data will be operated on)

Hierarchical Resources

- A *place* (X10, UPC++) or *locale* (Chapel, HCAF) represents a location in the machine
  - Includes memory and/or execution resources
- Hierarchical places model hierarchy of resources

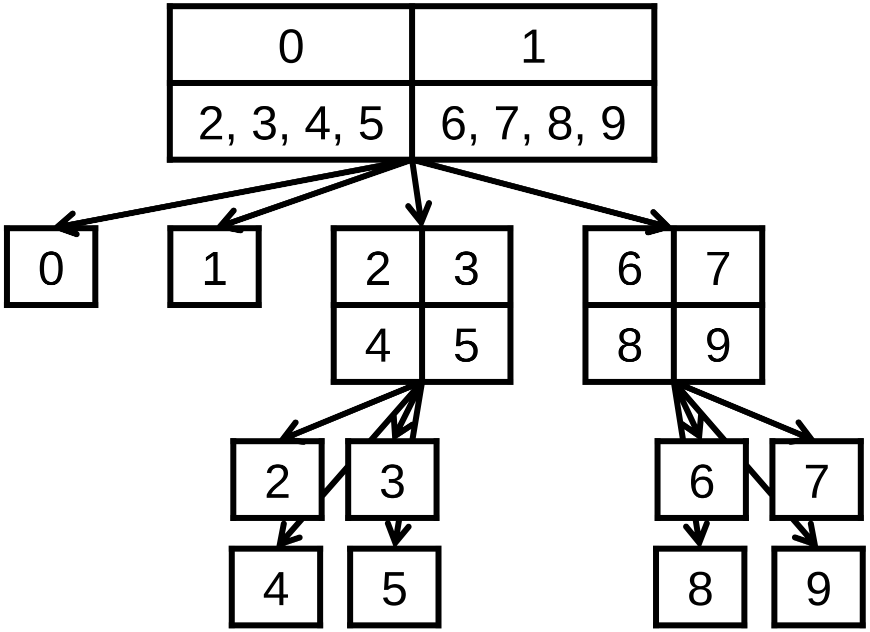




- Places can have memory units, execution units, or both
  - e.g. cache hierarchy modeled using memory-only places

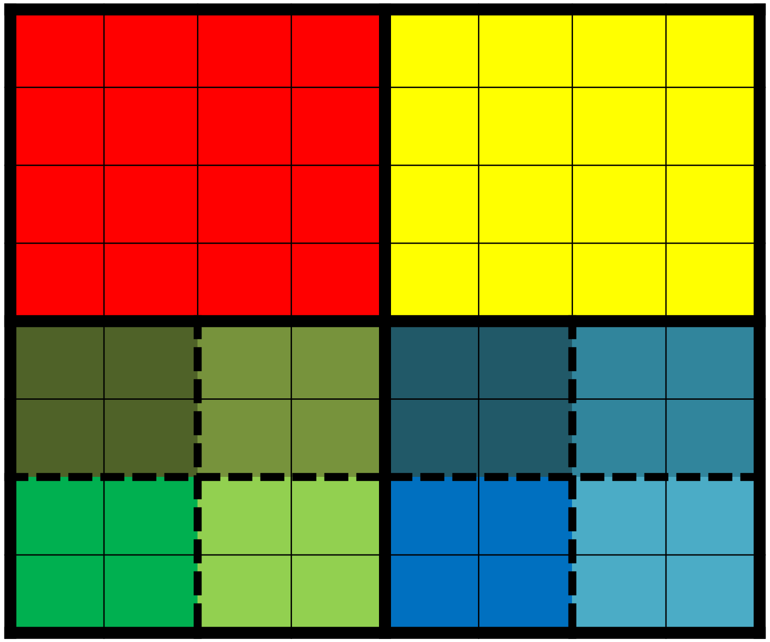
Data Hierarchy

- *Data hierarchy*: full hierarchical structure of data
  - Encompasses hierarchical teams and places
  - Allow synthesis from hierarchical teams, places, or both
- Multidimensional hierarchy required in order to match multidimensional data structures



Hierarchically Tiled Arrays

- Hierarchically Tiled Arrays (HTAs) are well-suited to managing hierarchy in data-parallel programs



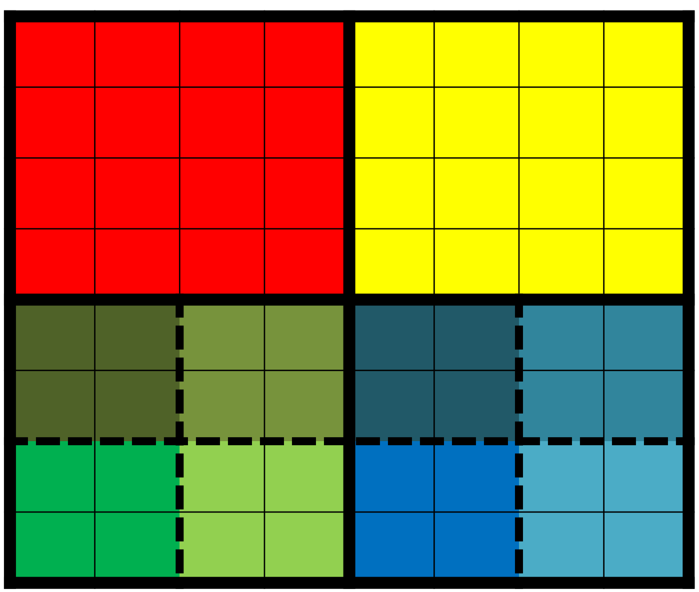
- Likely to be useful as distributed data structure in SPMD
  - Support global-view/team-view collective operations
  - Also support local-view computation

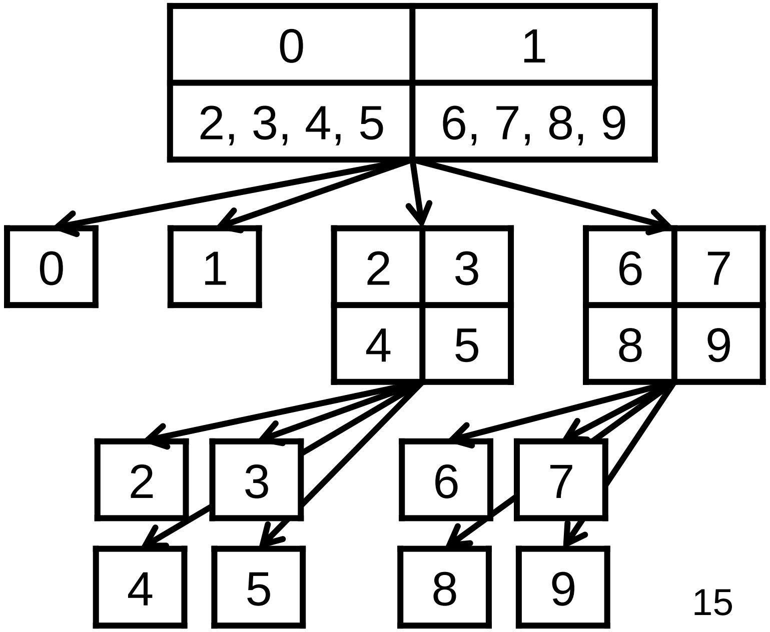
HTA Creation

- An HTA is created over a rectangular index space and a data hierarchy

```
hta<T, N> array(RD(PT(0, 0), PT(8, 8)),
                     data_hierarchy);
```

- Support block-cyclic and user-defined distributions, ghost/shadow regions, and replication for .5D algorithms





HTA Operations

- Access sub-tile (e.g. bottom-left tile)

```
array(1, 0)(1, 0)
```

- Access element

```
array[PT(7, 0)]
array(1, 0)[PT(7, 0)]
array(1, 0)(1, 0)[PT(7, 0)]
```

- Collective operations over tile or slice of HTA

```
array(1, 0).reduce(op)
array.slice(1, 1).map_reduce(mop, rop)
```

- Update ghost regions

```
array.update()
array.async_update()
```

Summary

- Hierarchical teams have been successful in expressing hierarchical algorithms and mapping execution onto hierarchical machines in SPMD programs
- Hierarchical places provide an abstraction of the resources in a machine
- Hierarchically Tiled Arrays (HTAs) proven to be valuable in data-parallel programming, likely will be in SPMD as well
- We are working on unifying these concepts in the DEGAS project
  - UPC++ at LBL, HCAF at Rice
  - In the process of finalizing design/interface, starting on implementation