EECS
Electrical Engineering and Computer Sciences

BERKELEY PAR LAB

PARALLEL COMPUTING LABORATORY

Three Challenges and Three Solutions for Exascale Computing

Amir Kamil and Katherine Yelick
UC Berkeley/LBNL

June 28, 2012

Three Challenges and Solutions

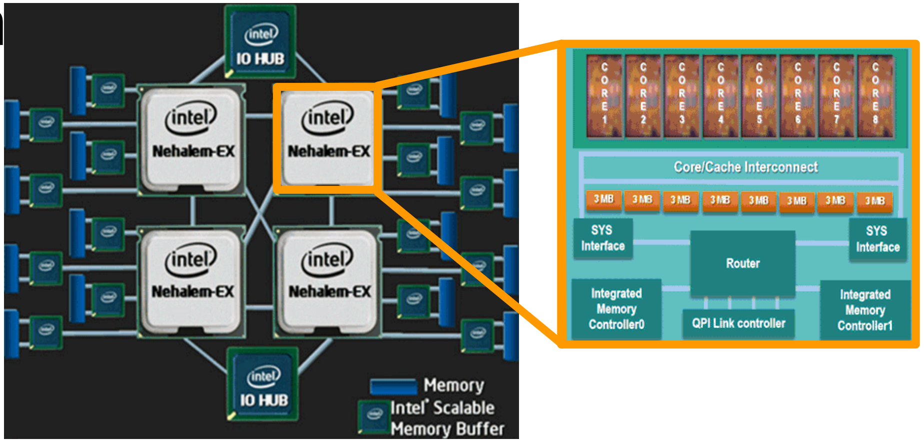
- Three challenges
  - Hierarchy
  - Heterogeneity
  - Resilience
- Three solutions
  - Programming models
  - Compiler/runtime infrastructure
  - Domain-specific libraries, languages, and specializers

EECS
Electrical Engineering and Computer Sciences

Hierarchy Challenge

BERKELEY PAR LAB

- Locality essential to achieving good performance at large scale, minimizing energy use
- Parallel locality no longer a binary value (local vs. not local)
  - Non-uniform memory access (NUMA) within single shared-memory node
  - Manycore systems may have multiple levels of NUMA-n

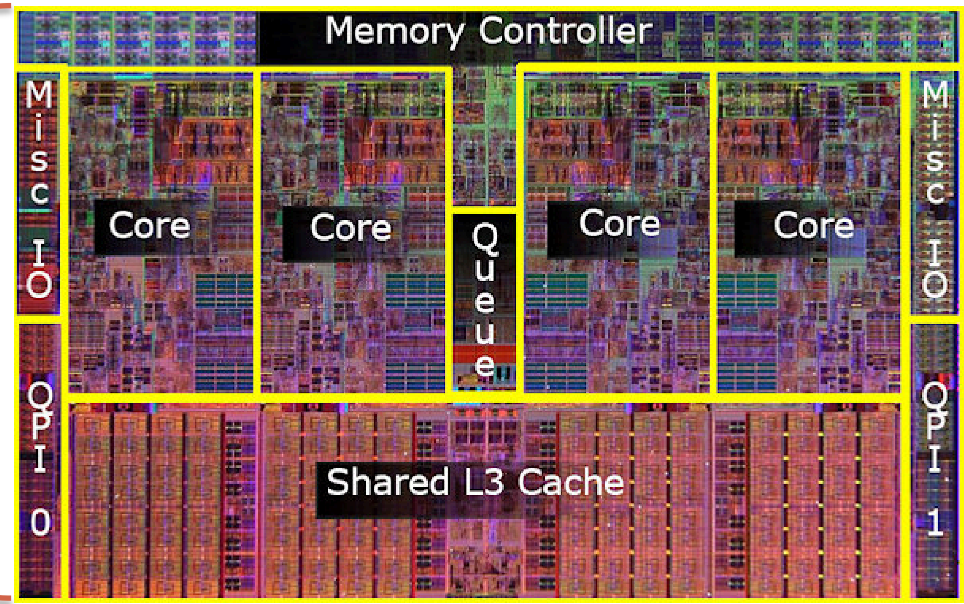


Heterogeneity Challenge

- Machines composed of heterogeneous components due to performance vs. energy tradeoffs

Cell phone processor
(0.1 Watt, 4 Gflop/s)

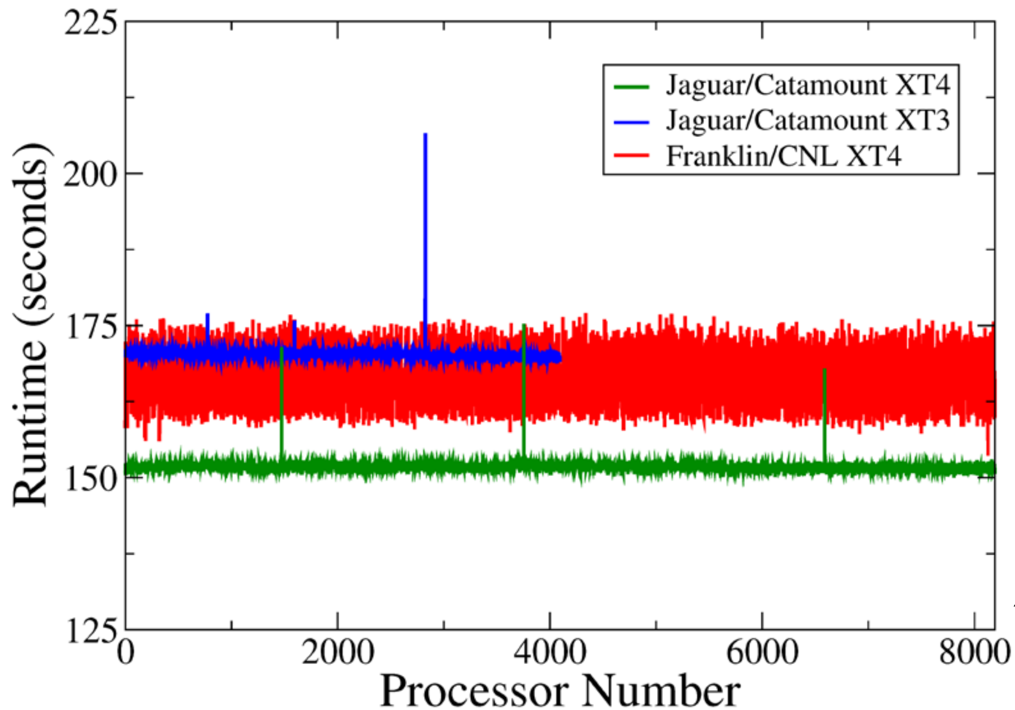
Server processor
(100 Watts, 50 Gflop/s)



- Components may have different capabilities (e.g. accelerators) or same capabilities at different performance and energy points
  - 3 of the top 5 machines in 11/11 include GPUs

Resilience Challenge

- Increasing scale means increasing probability of component failure during a program run
- Tradeoff between power consumption and error rates at the chip level increases likelihood of undetected errors



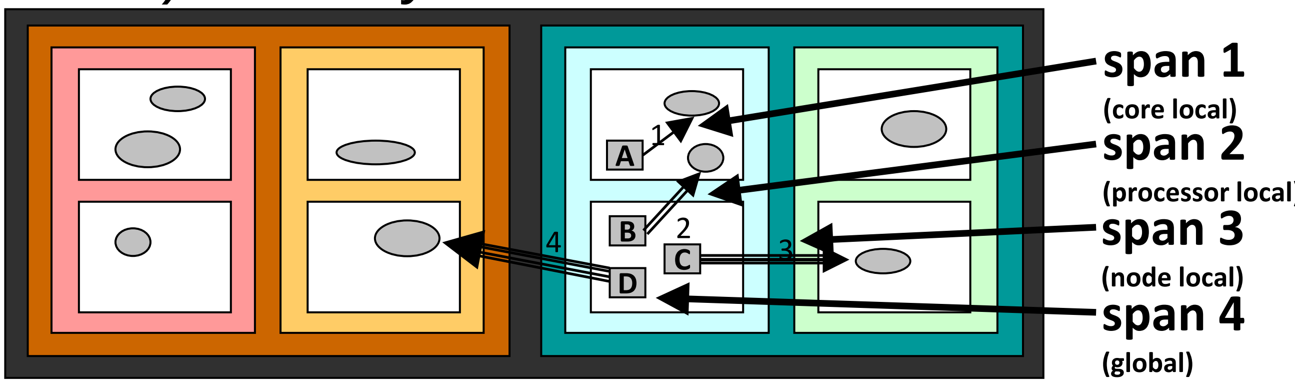
Van Straalen, et al, *Scalability Challenges for Massively Parallel AMR Applications*, IPDPS'09.

Three Solutions

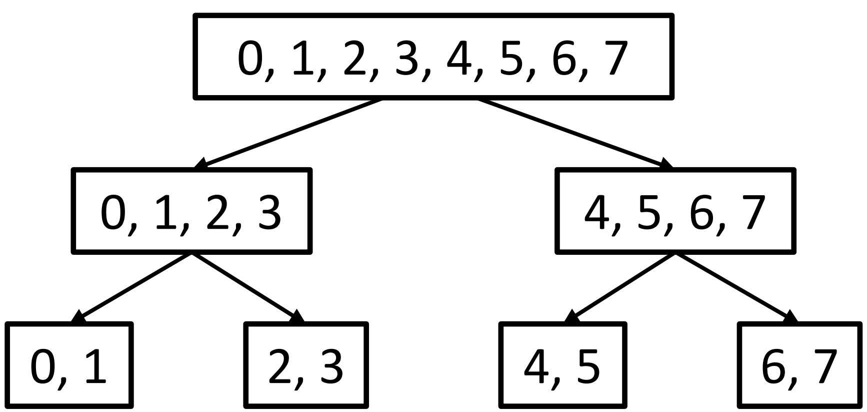
- Expose problems to user in the programming model
  - Force each user to deal with the problems themselves
- Generic solutions in the compiler, runtime, and hardware
- Domain-specific solutions in libraries, languages, and specializers
  - Expert programmers solve the problems

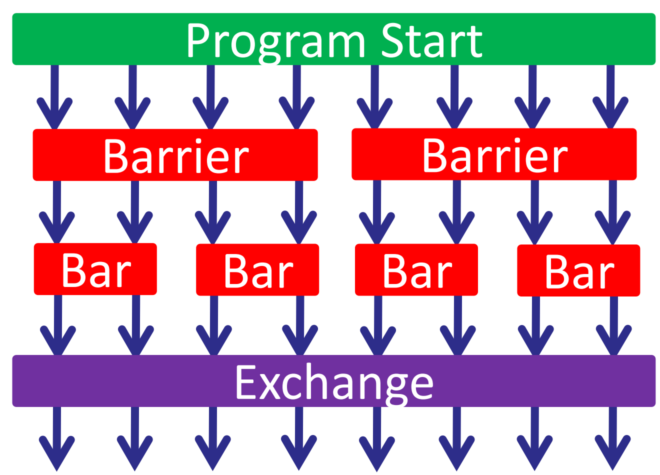
Hierarchical Programming Models

- Programming model solutions for hierarchy
  - Hierarchical partitioned global address space (HPGAS) memory model



  - Recursive single-program, multiple data (RSPMD) execution model

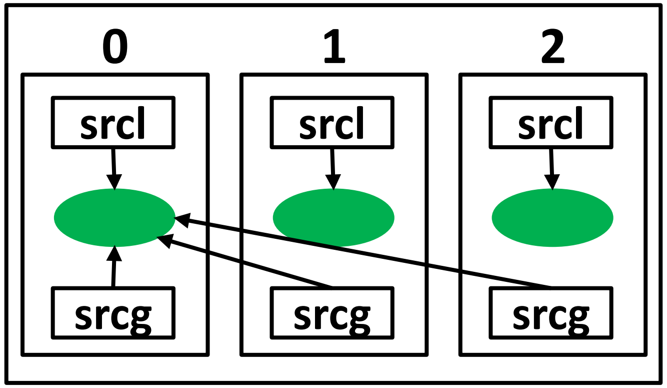




Partitioned Global Address Space

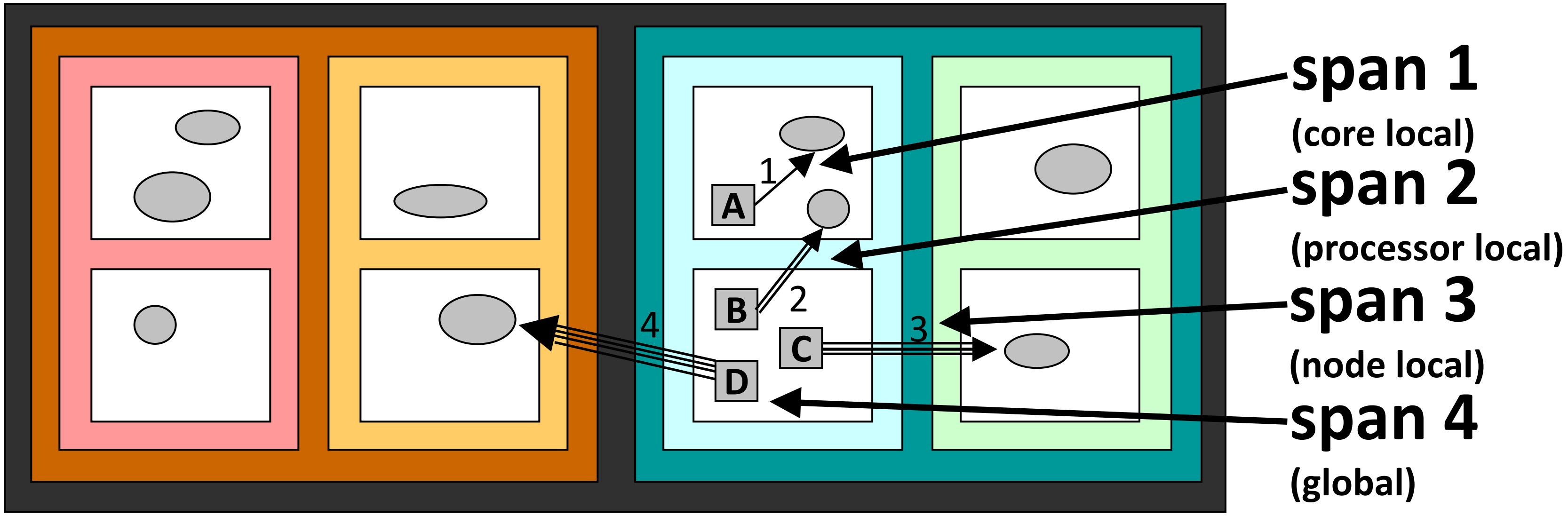
- Partitioned global address space (PGAS) abstraction provides illusion of shared memory on non-shared memory machines
- Pointers can reference local or remote data
  - Location of data can be reflected in type system
  - Runtime handles any required communication

```
double[1d] local srcl = new double[0:N-1];
double[1d] srcg = broadcast srcl from 0;
```



Hierarchical PGAS

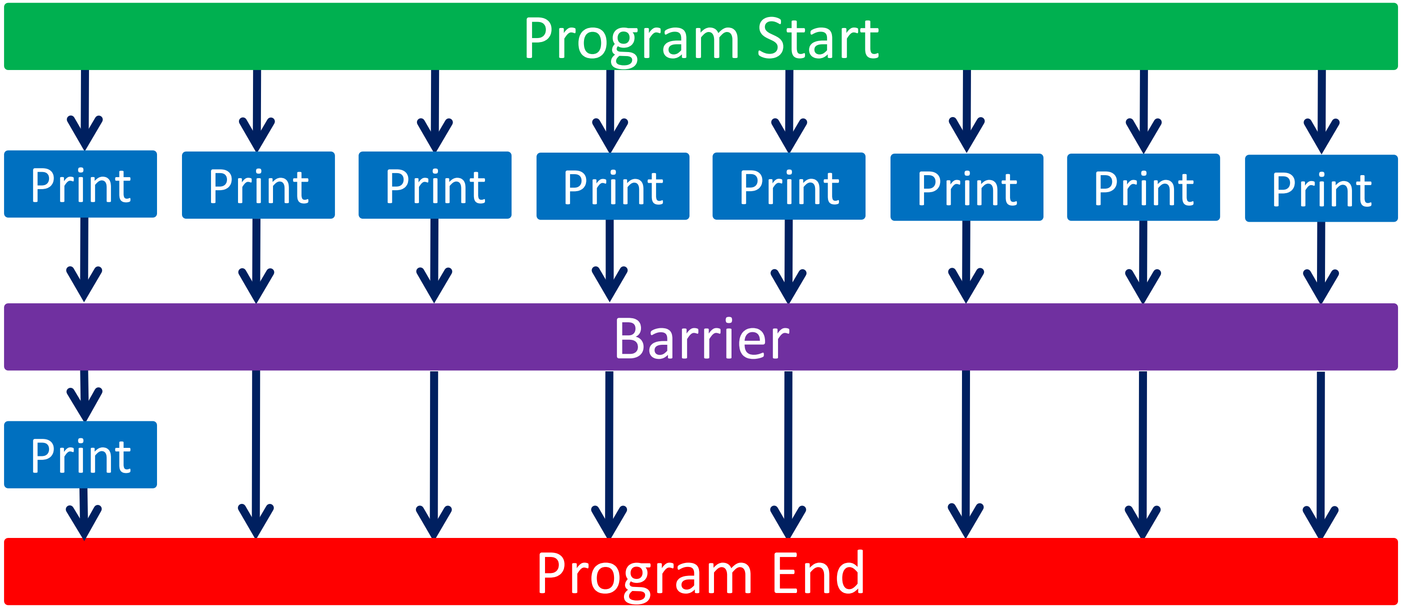
- PGAS model can be extended to hierarchical arrangement of memory spaces
- Pointers have varying *span* specifying how far away the referenced object can be
  - Reflect communication costs
- Pointer span can be inferred by compiler through hierarchical pointer analysis



Single Program, Multiple Data

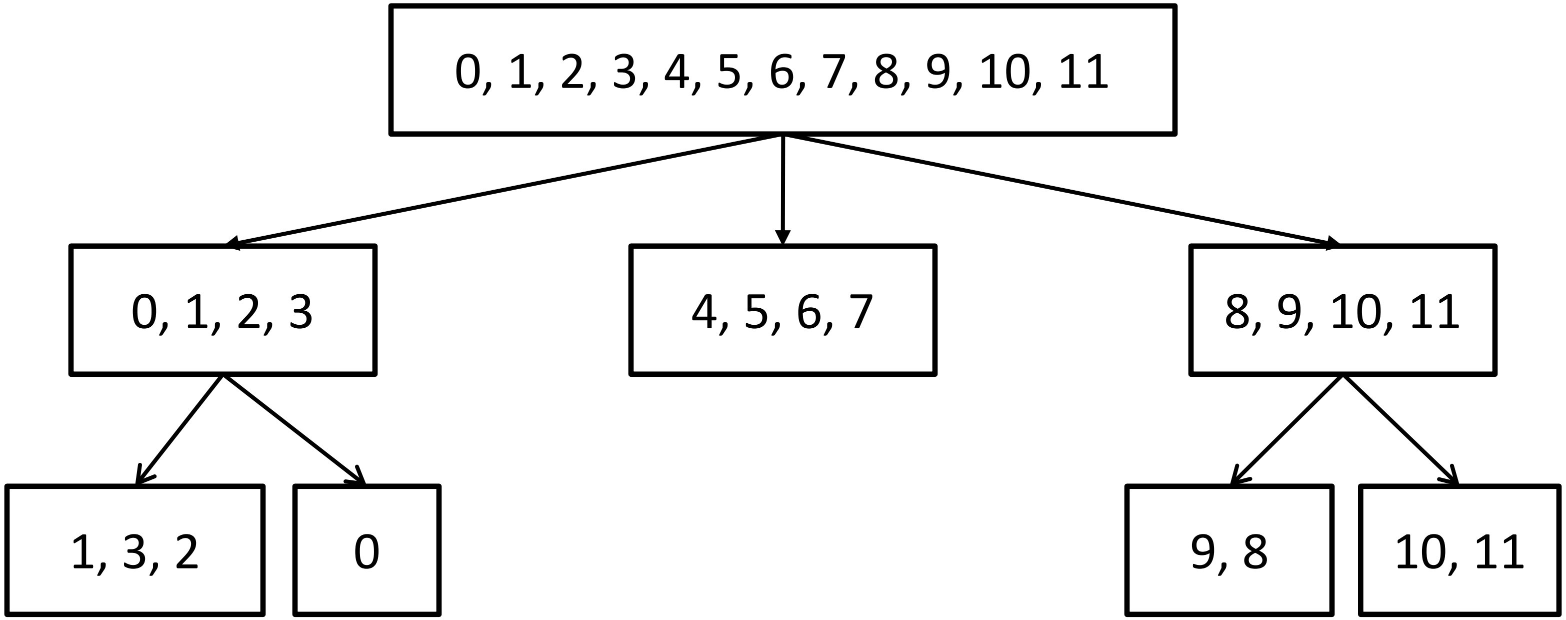
- Single program, multiple data (SPMD): fixed set of threads execute the same program image

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



Recursive SPMD

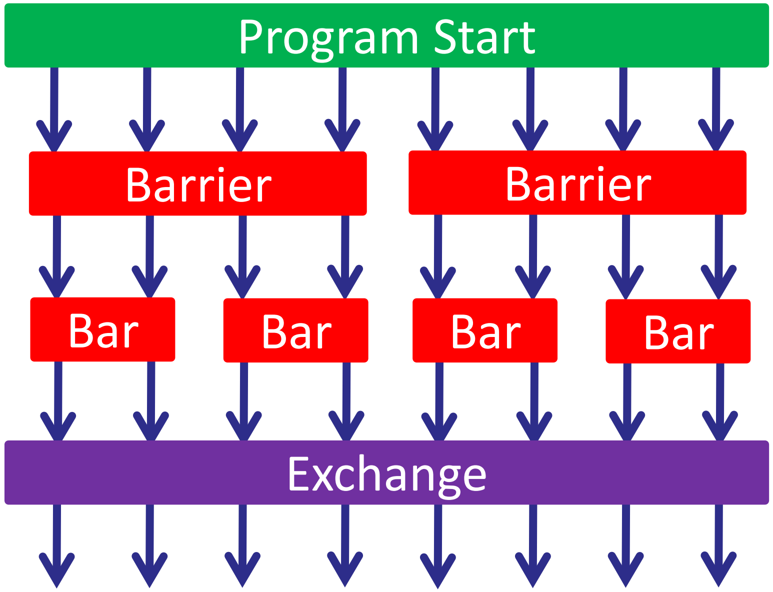
- Threads recursively subdivided into smaller teams in tree-like structure
  - Allow arbitrary hierarchies (e.g. unbalanced trees)
  - Can match machine structure



Language Constructs

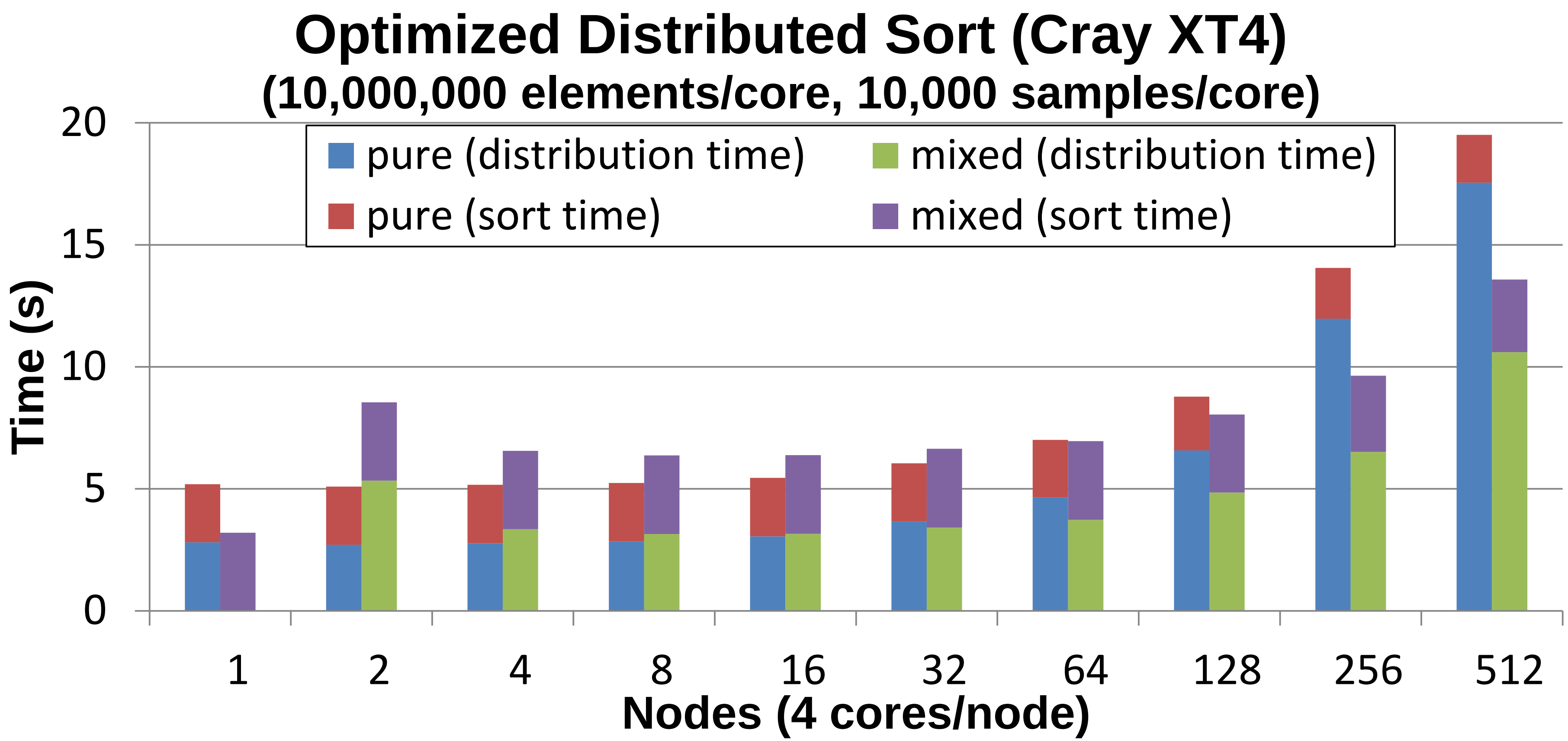
- New language constructs for assigning tasks or data to teams
  - Lexical scope prevents some types of deadlock, dynamic checks prevent others

```
teamsplit(T) {
  Ti.barrier();
  teamsplit(T2) {
    Ti.barrier();
  }
}
arr.exchange(data);
```



Programming Model Advantages

- RSPMD allows easy expression of hierarchical algorithms
  - Inherent hierarchy such as divide and conquer
  - Optimizations for hierarchical machines

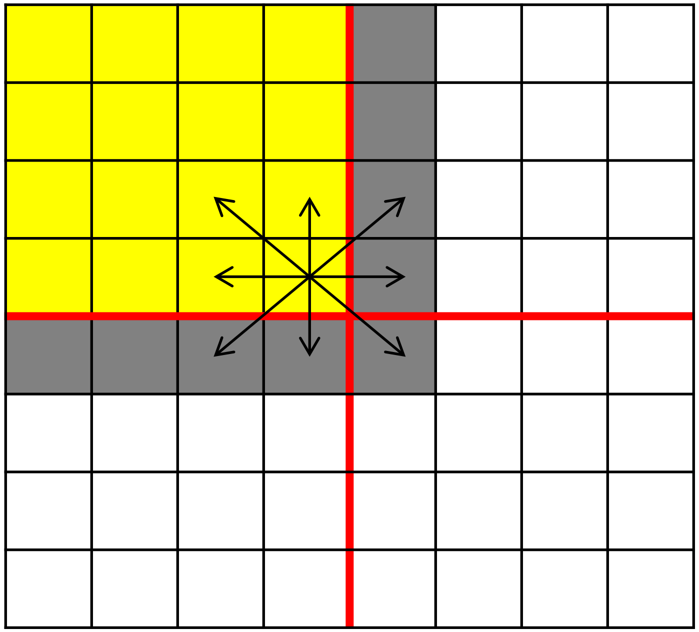


Programming Model Disadvantages

- Forces user to manually perform hierarchical locality optimizations
  - May be machine-specific and not generalize to arbitrary machine structures
- Algorithmic decomposition may not match machine structure
  - Matrix-vector multiplication with 2D decomposition requires row and column teams
    - Both can’t map to low levels in machine hierarchy

Other Approaches to Hierarchy

- Compiler/runtime ideas
  - Pointer analysis for HPGAS can be extended to RSPMD as well
  - Can use analysis to estimate communication costs between threads and map threads to machine
  - Dynamic analysis can increase precision at low cost
- Domain-specific ideas
  - Common communication patterns can be optimized in a library or specializer
    - Dense grid applications generally use static ghost zones, resulting in regular, repeated communication



Summary

- Hierarchical programming models simplify expression of hierarchical algorithms and enable good performance on hierarchical machines
- Need to be combined with compiler/runtime and domain-specific solutions to further improve productivity and performance
- We believe that all three challenges (hierarchy, heterogeneity, fault-tolerance) require a combination of programming model, compiler/runtime, and domain-specific solutions