A Type and Effect System for Deterministic Parallel Java

Robert Bocchino, Vikram Adve, Danny Dig, Sarita Adve, Stephen Heumann, Rakesh Komuravelli, Jeffrey Overbey, Patrick Simmons, Hyojin Sung, Mohsen Vakilian

http://dpj.cs.uiuc.edu/

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Deterministic Execution

Many parallel programs are (intended to be) deterministic

- Non-interactive computation
- Accept input, compute, produce output
- Parallelism for *performance*, not part of *specification*

Same input always produces same output

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It would help if our programming languages could guarantee deterministic execution

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Benefits of Guaranteed Determinism

Can reason "almost sequentially"

- Sequential semantics, parallel performance model

No subtle parallelism bugs

- No data races or deadlocks
- No complex memory models

Simpler testing

- Only one output to check per input
- Sequential to parallel port is easier

Simpler bug reproduction and debugging

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The Bad News

Some languages do guarantee determinism

- Functional, SIMD, explicit dataflow

But mainstream, general-purpose languages do not

- Imperative, OO languages (Java, C++, C#)

Expressive features obscure data flow

- Pointers/references to mutable objects
- Reference aliasing
- Inheritance and polymorphism

Deterministic Parallel Java (DPJ)

Modern object-oriented language

- We used Java because it's clean and safe
- Ideas apply to other OO languages (C++, C#) as well

Fork-join style of parallelism

- `foreach` loop, `cobegin` block
- Additional control constructs are future work

Type and effect system ensures noninterference

- Disallow conflicting operations between parallel tasks

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Type and effect system ensures noninterference

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Guarantees deterministic execution at compile time

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Contributions

Type system features for deterministic parallelism

- Region path lists for effect shapes and subtyping
- Novel array typing
  - Index parameterized arrays for parallel updates through references
  - Owner regions + library classes for divide and conquer recursion
- Support for commutative operations on concurrent data structures

Language description

Formal definition and soundess proof

Empirical evaluation

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Outline

Regions and Effects

New Type System Features

Evaluation

Conclusion

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See our paper for more details

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See our technical report for full definitions and proofs

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Regions and Effects

Regions

- A *region* is a name for a set of memory locations
- Programmer assigns regions to fields and array cells

Effects

- An *effect* is a read or write operation on a set of regions
- Programmer summarizes effects of method bodies

Compiler checks that

- Effect summaries are correct
- Parallel sections are noninterfering

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Documents side effects
Supports modular checking of noninterference

Example: A Pair Class

```
class Pair {
  region Fst, Snd;
  int fst in Fst;
  int snd in Snd;
  void setFst(int fst) writes Fst {
    this.fst = fst;
  }
  void setSnd(int snd) writes Snd {
    this.snd = snd;
  }
  void setBoth(int fst, int snd) {
    cobegin {
      setFst(fst); /* writes Fst */
      setSnd(snd); /* writes Snd */
    }
  }
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```

Pair		
Pair.Fst	fst	3
Pair.Snd	snd	42

Declaring and using region names

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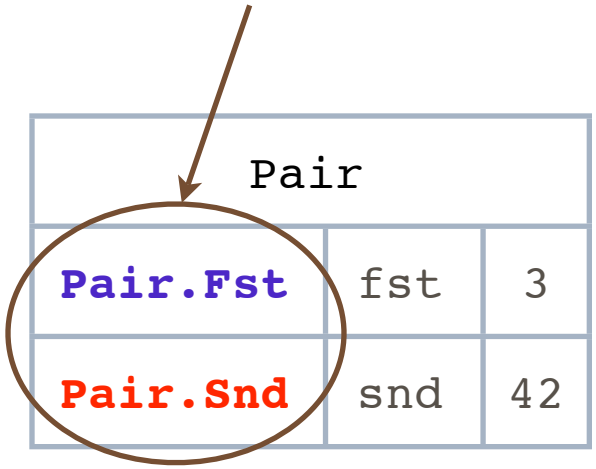
```

Region names have static scope (one per class)



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Writing method effect summaries

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Expressing parallelism

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Region Parameters

```
class SimpleTree<region P> {
  region L, R;
  int data in P;
  SimpleTree<L> left = new SimpleTree<L>();
  SimpleTree<R> right = new SimpleTree<R>();
  void updateChildren()
    cobegin {
      left.data = 0; /* writes L */
      right.data = 1; /* writes R */
    }
  }
}
```

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Class is parameterized by region P

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Field data resides in P

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Types provide actual regions for computing effects

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Distinguish different object instances

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Important Parallel Patterns

Pattern	DPJ Support

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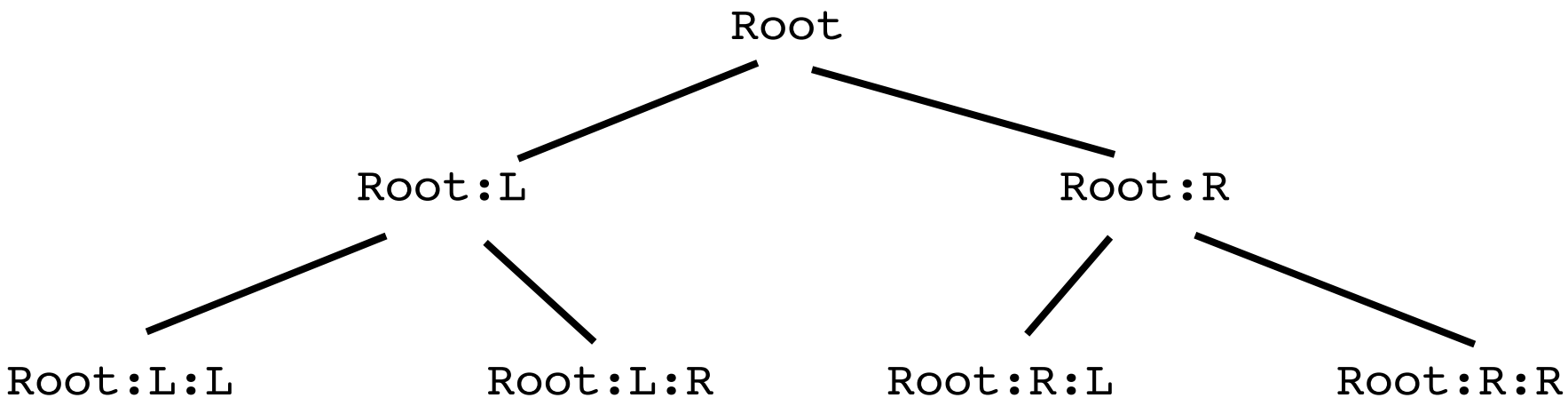
No previous type-based system supports any of these patterns

1. Region Path Lists (RPLs)



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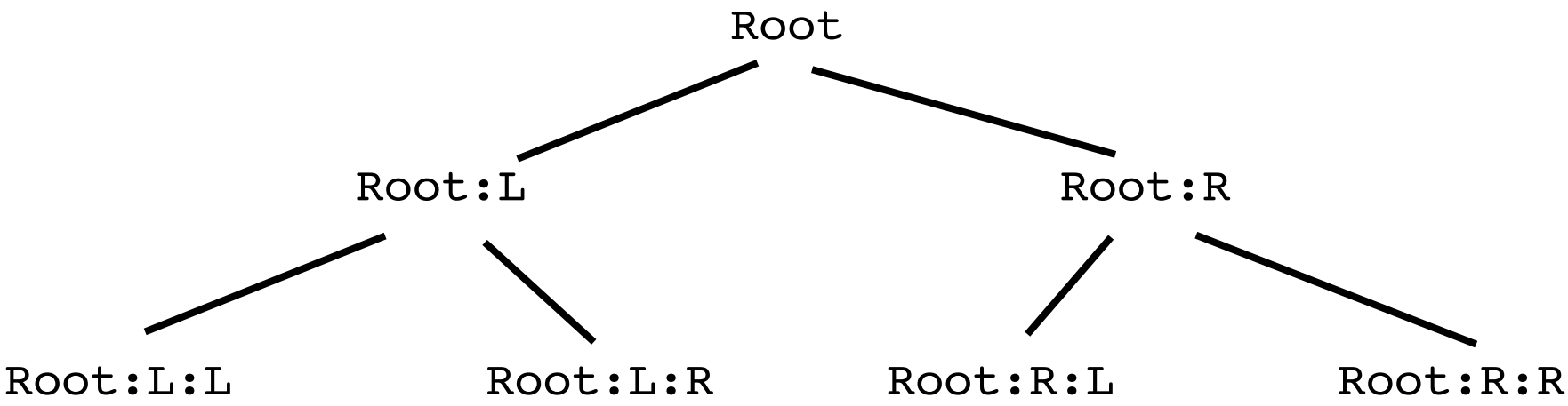

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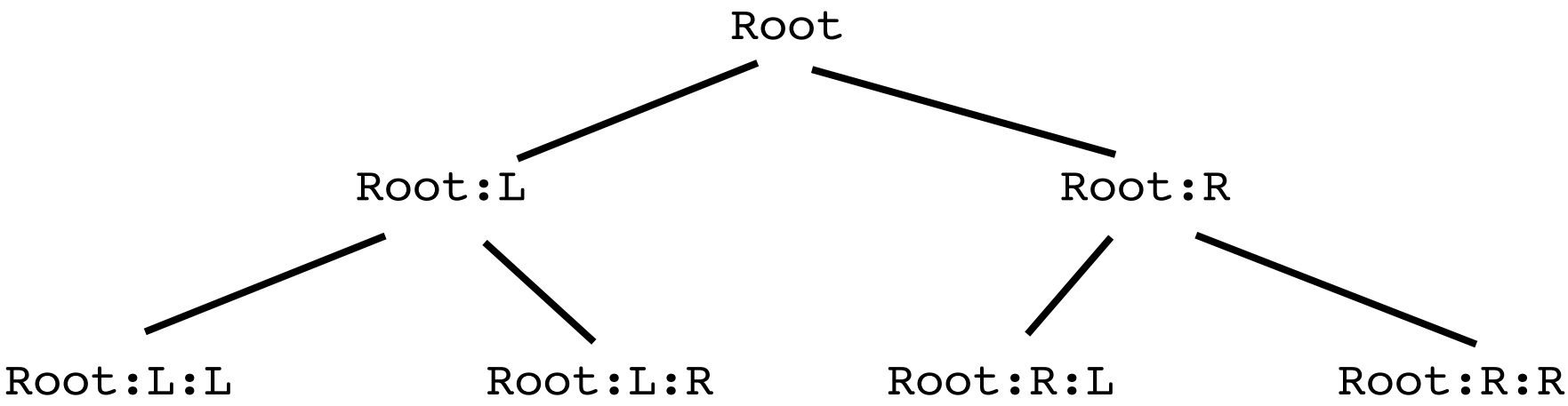

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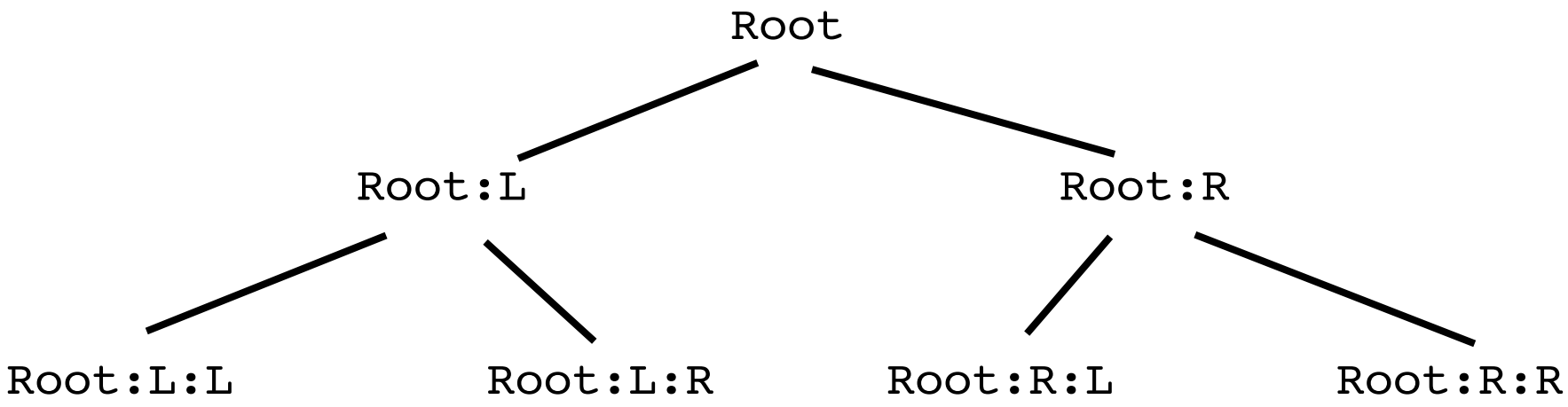

`Root:L:R` *is a Region Path List, or RPL*

RPLs naturally form a tree

`Root:L:R` *is a child of* **`Root:L`**

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Using RPLs to Write Types

```
class Tree<region P> {
  region L, R;
  int data in P
  Tree<P:L> left in P:L;
  Tree<P:R> right in P:R;
  ...
}
```

Using RPLs to Write Types

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In the source code, RPLs can begin with parameters

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P=Root	
data	Root
left	Root:L
right	Root:R

P=Root:L	
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P=Root:R	
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left	Root:R:L
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In the dynamic semantics, parameters are erased via left-recursive substitution

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    ++data; /* writes P */
    cobegin {
      /* writes P:L:* */
      if (left != null) left.increment();
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Method effect summary

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Effect inferred from type + summary

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P:L:* ⊆ P:* *(inclusion)*

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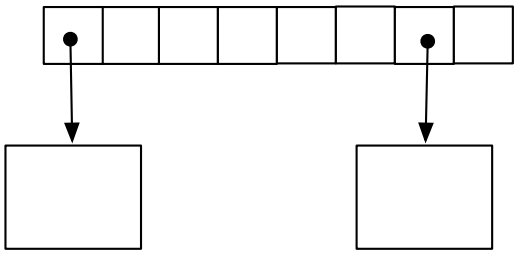
$\mathtt{P:L:*} \subseteq \mathtt{P:*}$ *(inclusion)*

$\mathtt{P:R:*} \subseteq \mathtt{P:*}$ *(inclusion)*

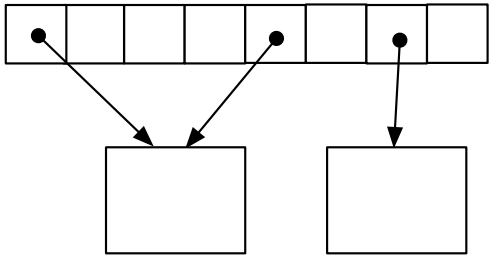
$\mathtt{P:L:*} \cap \mathtt{P:R:*} = \varnothing$ *(disjointness)*

2. Updating Objects through an Array

Key property is disjointness of references



Disjoint



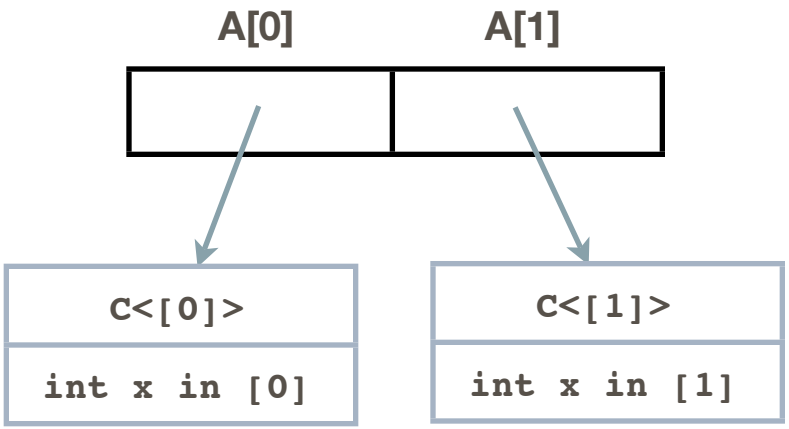
Non-disjoint

DPJ provides a novel array type `C<[i]>[]#i`

- Region `[i]` is parameterized by the index variable `i`
- Cell *i* of array `A` has type `C<[`*i*`]>`
- If $i \neq j$, then `A[`*i*`]` $\neq$ `A[`*j*`]`

Index-Parameterized Arrays

```
class C<region P> {
  int x in P
  void update() writes P {
   ...
  }
  ...
}
```



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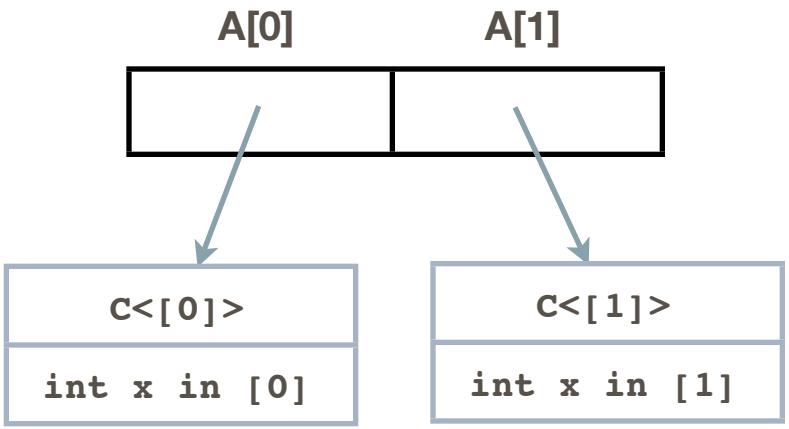

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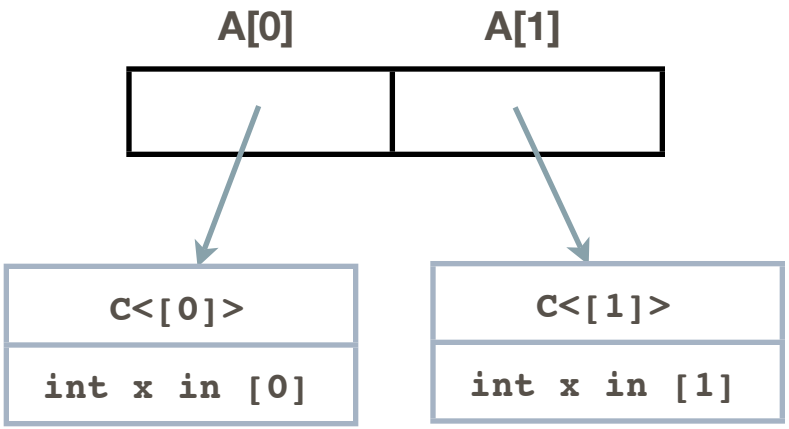
Field is placed in parameterized region



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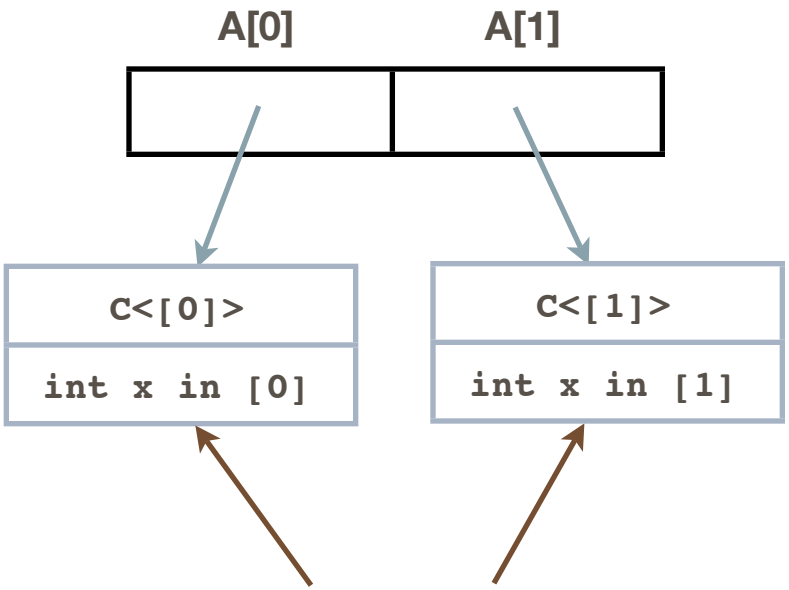

Objects in different array cells are created with different regions

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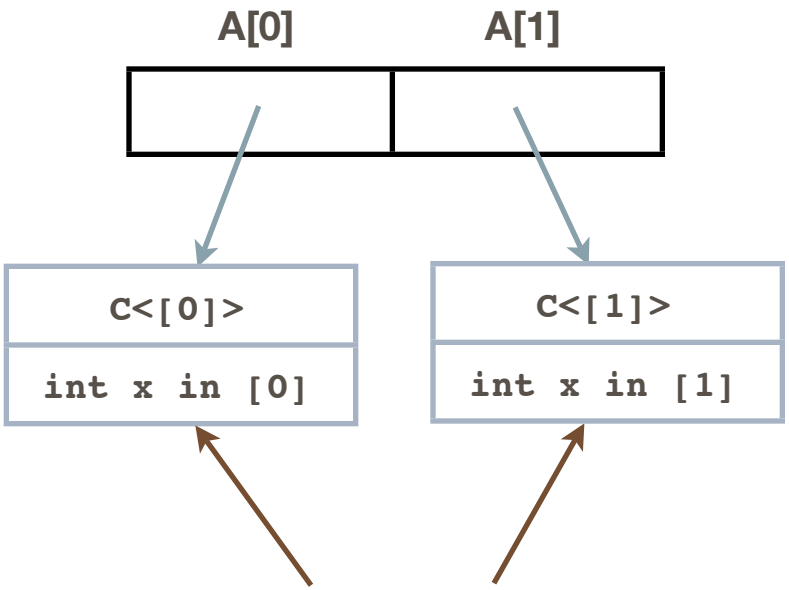
Field is placed in parameterized region



Objects in different array cells are created with different regions

A[0].update() and A[1].update() are noninterfering

3. Parallel Divide and Conquer

Library classes express array partitioning

- `DPJArray`: Represents a subrange "view" of a Java array
- `DPJPartition`: Collection of disjoint subarrays

Type system enforces noninterference of effect

- *Owner region* (similar to object ownership) + RPLs
  - Associates partition with local variable
  - Supports multiple partitions of the same array
- Each subarray in a partition resides in a distinct region
- Recursion makes an array into a tree of regions

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Array Partitioning Example

```
static <region R>void quicksort(DPJArray<R> A) writes R:* {
  int p = quicksortPartition(A);
  /* Chop array into two disjoint pieces */
  DPJPartition<R> segs = new DPJPartition<R>(A, p);
  cobegin {
    quicksort(segs.get(0) /* DPJArray<segs:[0]:*> */ );
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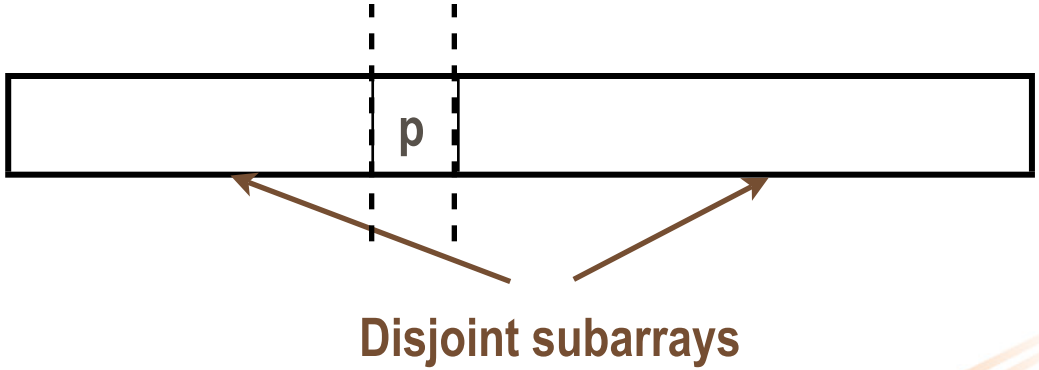
  }
}
```



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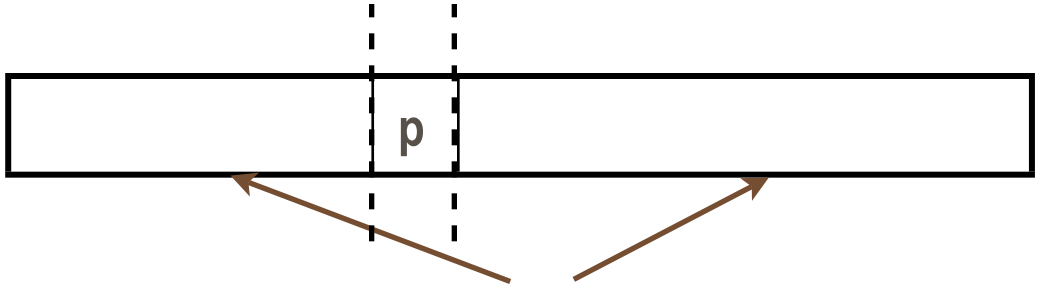

Disjoint subarrays

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```
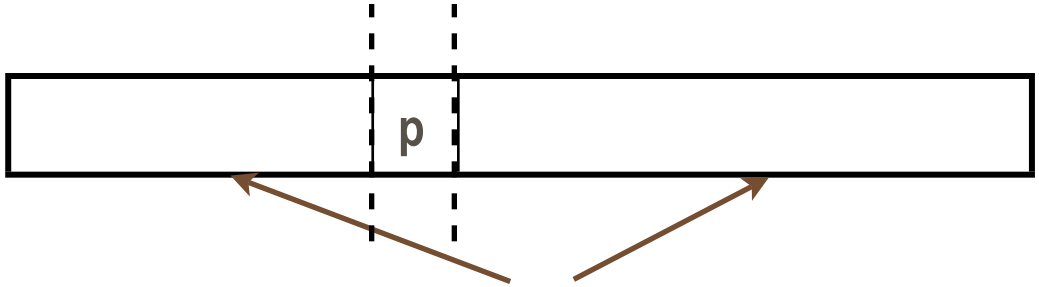

Subarrays



Disjoint subarrays

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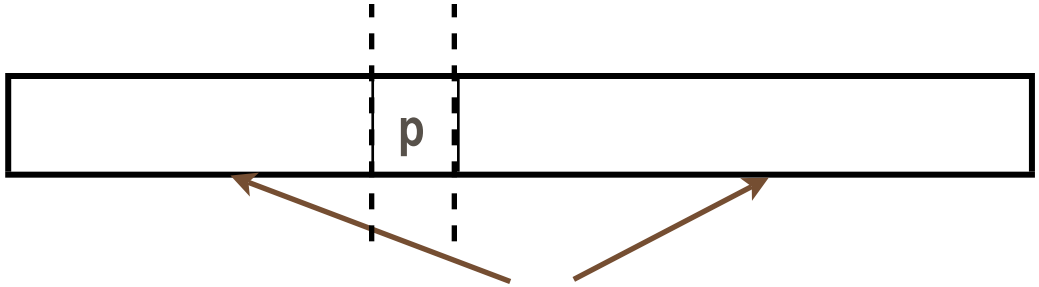
Array Partitioning Example

Partition

```
static <region R>void quicksort(DPJArray<R> A) writes R:* {
  int p = quicksortPartition(A);
  /* Chop array into two disjoint pieces */
  DPJPartition<R> segs = new DPJPartition<R>(A, p);
  cobegin {
    quicksort(segs.get(0) /* DPJArray<segs:[0]:*> */ );
    quicksort(segs.get(1) /* DPJArray<segs:[1]:*> */ );
  }
}
```

Subarrays

RPLs with owner regions



Disjoint subarrays

4. Commutativity Annotations

```
interface Set<type T, region R> {
    commutative void add(T e) writes R;
}
```

Annotation is

- Provided by library programmer
- Trusted by the compiler (not checked)

Annotation means

- `cobegin { add(e1); add(e2); }` is equivalent to one of
  - `add(e1); add(e2);`
  - `add(e2); add(e1);`
- Both sequences are equivalent

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Invocation Effect

```
foreach (int i in 0, n) {
    /* invokes Set.add with writes R */
    set.add(A[i]);
}
```

Noninterfering effects

- `invokes add with writes R`
- `invokes add with writes R`

Interfering effects

- `invokes add with writes R`
- `invokes size with reads R`

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Invocation Effect

```
foreach (int i in 0, n) {
    /* invokes Set.add with writes R */
    set.add(A[i]);
}
```

Noninterfering effects

- `invokes add with writes R`
- `invokes add with writes R`

Interfering effects

- `invokes add with writes R`
- `invokes size with reads R`

Invocation effect can also appear in method effect summary

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Outline

Regions and Effects

New Type System Features

Evaluation

Conclusion

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Implementation and Experiments

Implementation

- Extend Sun's javac compiler to do DPJ to Java translation
- Compile to ForkJoinTask Framework (Java 7)

Benchmarks

- IDEA encryption (Java Grande, 228 SLOC)
- Merge Sort (295 SLOC)
- K Means clustering (STAMP, 501 SLOC)
- Barnes-Hut force computation (SPLASH, 682 SLOC)
- JMonkey collision detection (1032 SLOC of large application)
- Monte Carlo financial simulation (Java Grande, 2877 SLOC)

Research Questions

1. Expressiveness

- Successful in expressing realistic parallel algorithms
- There are some limitations
  - Can't shuffle elements of an index-parameterized array

2. Usefulness of features

- All features described used in benchmarks

3. Porting effort

- Defaults allow incremental porting
  - JMonkey: Most of large application untouched
- Modified about 10% of total SLOC (most were types)
  - Effect inference [ASE 2009] improves this

4. Performance

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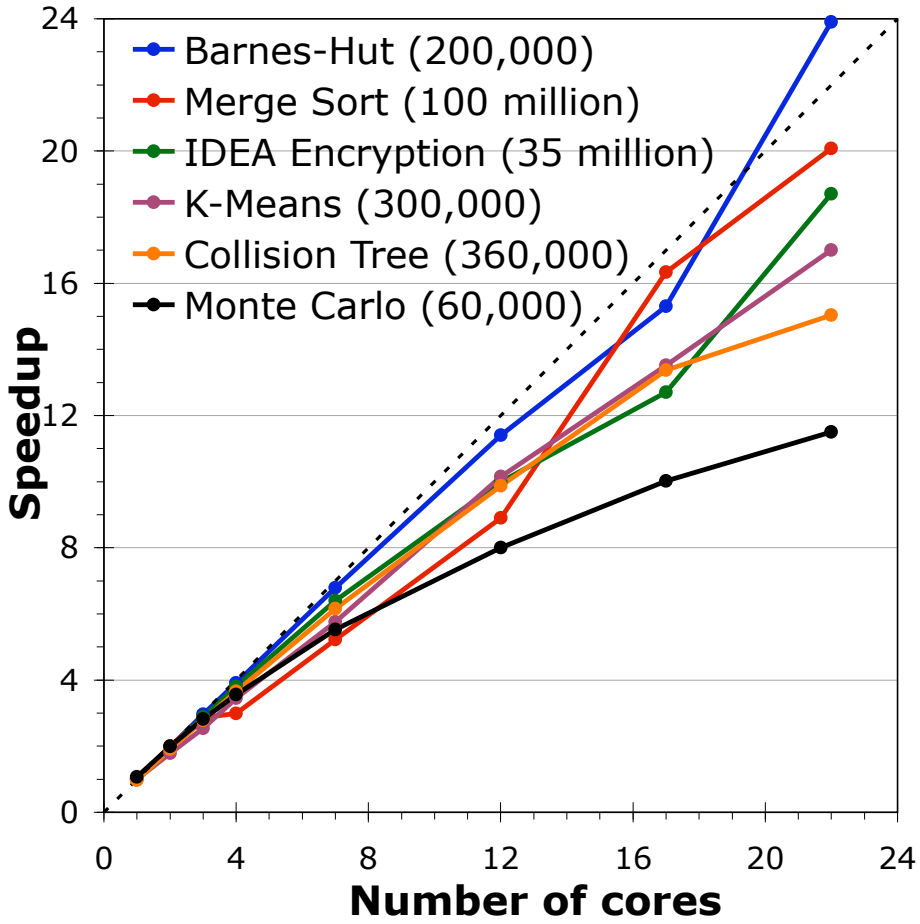
Performance Results



- DPJ enables good performance
- BH, Merge Sort showed near-ideal speedup on 16–22 cores
- IDEA, Monte Carlo, and BH nearly matched or beat handwritten threads

4 x 6 core x86 (Dell R900), 2GB main memory per core

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Conclusion

Deterministic parallel programming model

- Object-oriented language with references
- Compile-time determinism guarantee

Expressivity and performance

- Six realistic parallel codes
- Good performance
- Annotations useful and not too burdensome

Compiler will be available for download soon

http://dpj.cs.uiuc.edu/

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