Types, Regions, and Effects for Safe Programming with Object-Oriented Parallel Frameworks

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

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Parallel Frameworks Are Very Useful...

Provide generic algorithm such as map, reduce, scan

- User fills in missing pieces
- Overrides methods specified in framework API

Advantages

- Easy for user (write sequential code)
- Reusable code for common patterns
- Separation of concerns: parallelism vs. domain expertise

Real world examples are emerging

- Algorithm templates in TBB
- `ParallelArray` framework in Java

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...But They Are Also Dangerous!

User can provide *arbitrary method* for parallel execution

What if the user's method...

- Updates a global variable?
- Updates a collection of objects with duplicate elements?
- Follows a link from one object in a collection to another?
- Etc., etc.

***Current approach*: Informal, unchecked specification**

- "Don't do that!"
- This is not satisfactory

Goal: Make Frameworks Safer

Idea: Use *design by contract* for framework APIs

- Formally specify and check conditions on use
- This idea has been well studied for other specifications
  - E.g., make sure that you follow the server protocol
- But not for shared-memory parallel frameworks

Key challenges

- Ensure that containers don't have duplicate objects
- Constrain the effects of user-supplied methods
- Make the types and effects sound yet generic enough to be useful

Contributions

We build on Deterministic Parallel Java (DPJ)

- Rich region-based type and effect system
- Leverage type information already built into framework APIs

We show how to...

- Use DPJ "off the shelf" to write safe APIs for container frameworks
  - Use local parameters, set properties, etc. to constrain aliasing and effects
- Extend the DPJ type system to add generic types and effects
  - Effect variables, type region parameters
- Make different forms of verification interoperate
  - Use program logic or testing to verify framework *internals*
  - Use the type system to verify framework *uses*

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Outline

A Safe Container API Specialized to List Nodes

A Safe Container API with Generic Types and Effects

Verifying the Implementation

Evaluation

Conclusion

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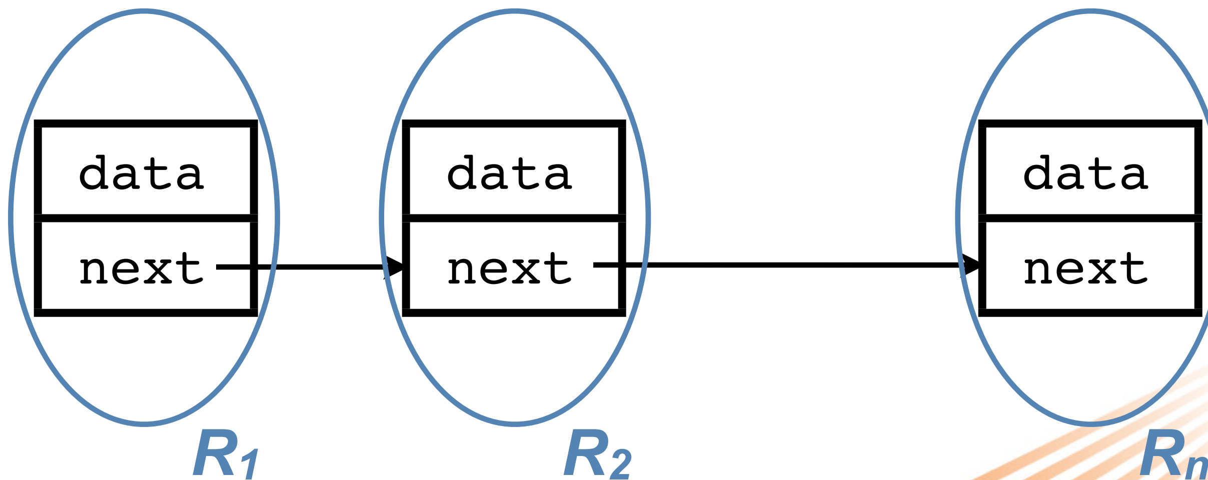
A DPJ List Node Class

Class is parameterized by region **R**

```
class ListNode<region R> {
  int data in R;
  ListNode<*> next in R;
}
```

Data resides in **R**

next can point to any **ListNode**



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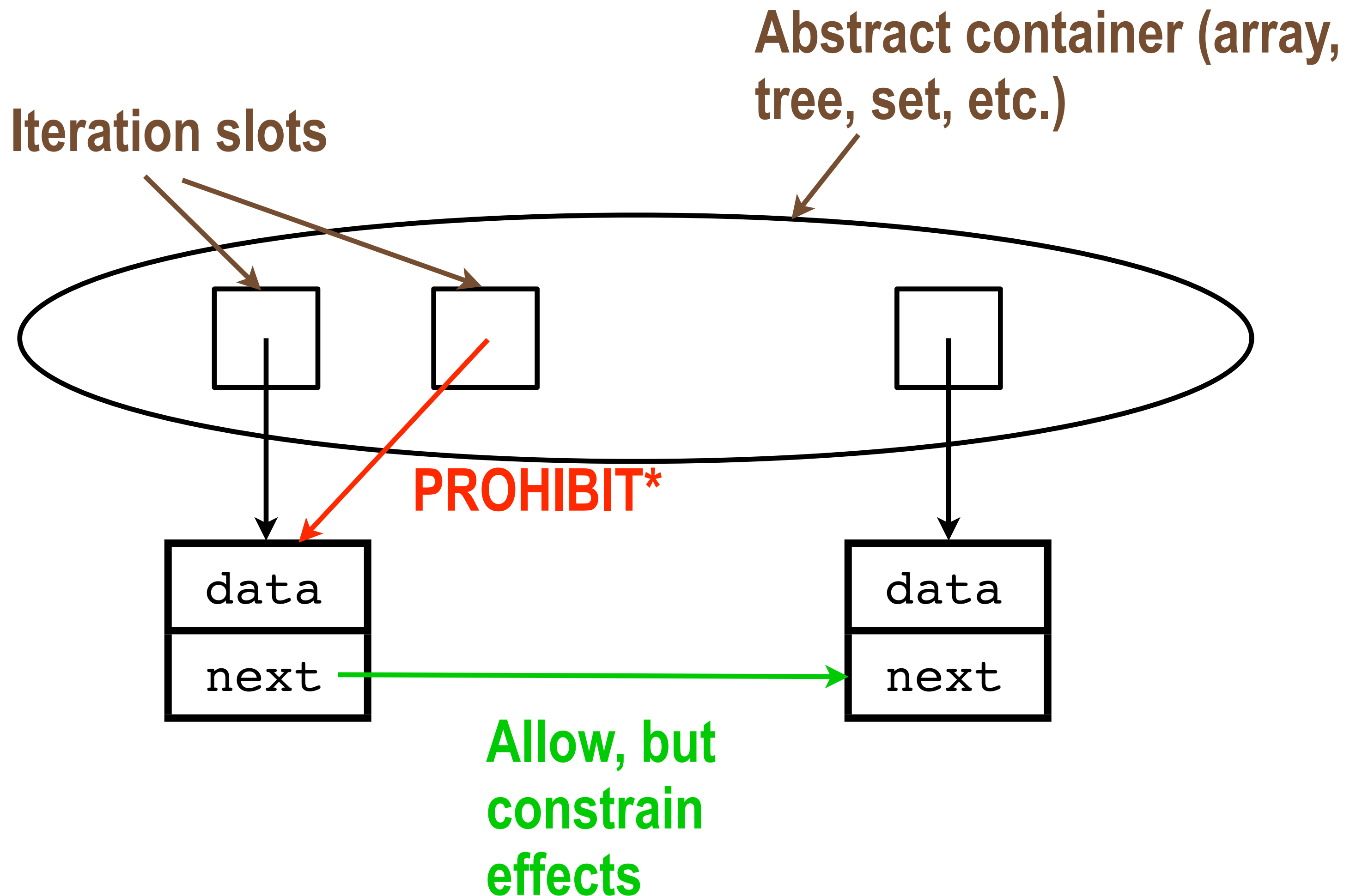
A List Node Container



*We say the container is *internally linear*

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Maintaining Linearity

Inductive argument based on API

- A container starts empty (trivially linear)
- Only API operations can change state (encapsulation)
- Every API operation is linearity-preserving

Kinds of API operations

- Adding elements
- Transforming elements
- Moving elements around (e.g., tree rebalancing)
- Deleting elements

Needs careful API design

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Strategies for Adding Elements

Making one linear container from another

- E.g., tree from array or set
- Constructor API says incoming container must be linear
- Special case in DPJ = *index-parameterized array*

Populating container with user-supplied factory method

- Framework calls method once on each slot
- API must ensure the "factory method" really returns a fresh object!

Backing container with a set

- Sets are linear by definition
- Container semantics gives linearity "for free"

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User-Supplied Factory Method

Framework API

```
public interface NodeContainer<region N, C> {
  public interface NodeFactory {
    public <region R>ListNode<R> create(int i) pure;
  }
  ...
}
```

In interface, return type uses method region parameter...

User Code

```
public class MyFactory implements NodeContainer.NodeFactory {
  public <region R>ListNode<R> create(int i) pure {
    return new ListNode<R>(i, null);
  }
}
NodeContainer<N,C> cont =
  new NodeArray<N,C>(new MyFactory(), 10)
```

...so in user implementation, returned object must be freshly created

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Reasoning About Effects

Need to constrain effects of user-supplied methods

- Method should update only object(s) it is given

Conceptually this is straightforward (ordinary DPJ)

- Each element gets its own region
- Interface requires that method write at most under that region

But there's a catch

- If regions appear in the API, we can't swap elements between slots
  - Assigning `ListNode`<r_1> to `ListNode`<r_2> is unsound
  - General problem for region-based type systems (including DPJ)
- So instead we use the method region parameter trick
  - Write API's types and effects in terms of parameter `R`
  - Hide actual regions bound to `R` from user of API

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Effects, Continued

Framework API

```
public interface NodeContainer<region N, C> {
  public void performOnAll(Operation op) reads C writes N:*;
  public interface Operation {
    public <region R>void operateOn(ListNode<R> node) writes R:*;
  }
  ...
}
```

Subclass relation constrains effects

User Code

```
public class MyOperation implements NodeContainer.Operation {
  public <region R>void operateOn(ListNode<R> node) writes R {
     ++node.data;  // OK, writes R
     ++node.next.data;  // ERROR, writes *
  }
}
container.performOnAll(new MyOperation());
```

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Why Does This Work?

Framework ensures slot *i* has type `ListNode`$<R_i>$ s.t.

- R_i is under `N`, the node region of the container
- R_i`:*` # R_j`:*` for i =/= j

Therefore:

- (a) Effects of `performOnAll` are bounded by `writes N:*`
  - ⟹ the summarized effects are correct in the framework API
- (b) Effects of `operateOn` on slot *i* are bounded by `writes` R_i`:*`
  - ⟹ the effects are disjoint for different slots

Notice that

- These “hidden regions” are invisible to the user
- We could not show (a) or (b) with the type system alone

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Generic Effects

***Problem*: Superclass effects constrain subclass effects**

- Required for sound reasoning with polymorphism
- But then superclass writer must “know” all future subclass effects
- This is unsatisfactory for frameworks

Solution*: Use *effect variables

- Parameterize classes, methods by effect variables `E`
- Write method effects using `E`
- Provide actual effects for `E` when classes, methods are *instantiated*

Technical challenges

- Sound subtyping (see paper)
- Effect constraints

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Generic Effects, Continued

Framework API

```
public interface NodeContainer<region N, C> {
  public interface Operation<effect E> {
    public <region R>void operateOn(ListNode<R> node)
      writes R:* effect E;
  }
  public <effect E | E # reads C writes N:* effect E>
    void performOnAll(Operation<E> op)
      reads C writes N:* effect E;
  ...
}
```

`Operation` is effect polymorphic

`performOnAll` constrains the effect of the supplied operation

User Code

```
public class MyOperation implements
  NodeContainer.Operation<pure> {
    public <region R>void operateOn(ListNode<R> node)
      writes R {
        ++node.data;
    }
}
cont.<pure>performOnAll(new MyOperation());
```

effects supplied by user code must obey constraints

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Generic Types

A container of list nodes is nice, but...

***Problem*: Must name region parameter of contained type**

- E.g., `void operateOn(ListNode<R> node) writes R:*;`
- Can't do this if we replace `ListNode<R>` with generic type `T`!

Solution*: Introduce *type region variables

- Kind of like C++ template template parameters
- Refer to the first *n* region arguments of a generic type argument

```
class C<type T<region R>>
```

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Generic Types, Continued

Framework API

```
public interface LinearContainer<type T<region R1>,
  region C> {
    public interface Operation<type T<region R2>,
    effect E> {
      public <region R3>void operateOn(T<R3> node)
        writes R:* effect E;
    }
    ...
}
```

User Code

```
public class MyOperation implements
  LinearContainer.Operation<ListNode<N>, pure> {
    public <region R4>void operateOn(ListNode<R4>
      node) writes R {
        ++node.data;
    }
}
cont.<pure>performOnAll(new MyOperation());
```

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Verifying the Implementation

Can use any desired method

- Testing
- Model checking
- Program logic

Full formal verification (proof) is future work

For now, sketch how to do it

- Use API to prove properties of framework internals
- Glue proved properties to the type system
- Properties + type system $\Rightarrow$ composite proof of noninterference

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Array Implementation

API, not assignment rules, constrains these types

```
public LinearArray<type T<region R>, region C> {
  T<R:*>[]<C> arr;
  ...
  public interface Operation<type T<region R2>,
  effect E> {
    public <region R3>void operateOn(T<R3> node)
      writes R:* effect E;
    }
  }
  public <effect E | E # reads C writes R:* effect E>
    void performOnAll(Operation<E> op)
      reads C writes R:* effect E {
        foreach (int i in 0, array.length)
          op.operateOn(arr[i]);
    }
  ...
}
```

Use type and effect constraints to push through "normal" DPJ proof for this loop

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Array: Verifying Type Constraints

Constraints: Want...

- `arr[`i`]` has type `T`<R_i>
- R_i`:*` # R_j`:*` if i =/= j

Proof: Inductive API argument (as for linearity)

- Trivial for fresh container
- Only API operations update state
- Each API operation preserves the property (e.g., permutation)

DPJ Proof

- Augment type system with predicate *disjoint-rgn(*z_i*,* z_j*)*
- Prove it using API constraints
- Use it to push through type-based proof

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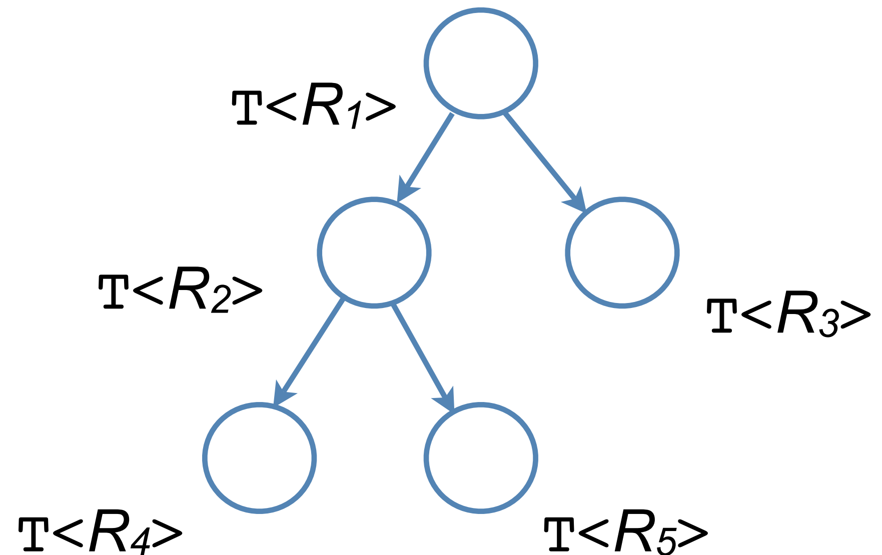
Tree Implementation

Same argument from API for data stored in nodes

Use logic to show

- Tree is a tree (shape)
- Parallel traversal touches disjoint nodes (traversal)

Replace recursive DPJ types with logic



R_i : * # R_j if i =/= j

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Evaluation Overview

Wrote two parallel frameworks

- Array (based on Java ParallelArray)
- Tree (from scratch, inspired by tree algorithms)

Wrote two parallel algorithms

- *Monte Carlo* (Java Grande) using array framework
- *Barnes-Hut center of mass* (JOlden, SPLASH) using tree framework

Performed qualitative assessment

- *Expressivity:* Can we write the algorithms efficiently?
- *Ease of use:* For application writers (i.e., framework users)

Frameworks

Array framework

- `create`: User-supplied factory method
- `withMapping`: Array-to-array mapping $T_1[\,] \rightarrow T_2[\,]$
  - User supplies elementwise mapping function $T_1 \rightarrow T_2$
- `reduce`: Array-to-object mapping $T[\,] \rightarrow T$
  - User supplies binary mapping $(T, T) \rightarrow T$

Tree framework

- `buildTree`: Build a tree from a linear container
  - User supplies index function that determines which child to visit
- `visitPO`: Recursive parallel postorder tree traversal
  - User supplies visit method to apply to each node

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Algorithms

Monte Carlo financial simulation

- Map-reduce pattern
- Create many tasks, operate on them in parallel, reduce them

Barnes-Hut center of mass computation

- Recursive, divide-and-conquer tree update
- Octtree represents points in space
- Traverse tree and update each node with center of mass of subtree

Qualitative Assessment

Expressivity

- Safe frameworks express these algorithms well
- Combining arrays (e.g., concatenation) would be hard

Ease of use for application writers

- Region and effect annotations for API are sometimes tricky
- But user effect arguments are simple
  - `pure` or one or two read effects

Compared with "ordinary" DPJ

- User-written types are simpler
- Assignments are less restricted (e.g., reordering array)
- Code is more verbose

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Conclusion

Safe frameworks can help parallel programming

We show how to...

- Use DPJ "off the shelf" to write safe framework APIs
- Make the types and effects generic with novel techniques
- Combine type-based and other verification in a modular way

Future work

- Verify framework implementations
- Explore whether any more "glue" is needed to do composite proofs