Safe Nondeterminism in a Deterministic-by-Default Parallel Language

Robert L. Bocchino Jr., Stephen Heumann, Nima Honarmand, Sarita Adve, Vikram Adve, *University of Illinois*

Adam Welc, Tatiana Shpeisman, Yang Ni, *Intel*

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

UPCRC Illinois
Universal Parallel Computing Research Center

Deterministic Parallel Java (DPJ)

Object-oriented parallel language

- Java is a nice research target
- Ideas apply to other OO languages as well

Guarantees determinism *at compile time*

- For given input, output is *schedule-independent*
- Programmer writes annotations (regions and effects)
- Compiler uses annotations to prove determinism
  - Simple analysis despite complex aliasing and data flow
  - Strong guarantee with no runtime overhead

Benefits and Costs of DPJ

Benefits

- Easier to reason about parallel code (like sequential code)
- Easier to test parallel code (one output per input)
- No subtle parallelism bugs (races, deadlocks)
- Simpler bug detection and debugging

Costs

- Programmer annotation burden
  - *Inferring annotations can help [M. Vakilian et al., ASE 2009]*
- Excludes nondeterministic algorithms by design
  - *We can add nondeterminism with some simple language extensions*
- Expressivity limitations even for deterministic codes
  - *Frameworks etc. can help*

UPCRC Illinois
Universal Parallel Computing Research Center

Benefits and Costs of DPJ

Benefits

- Easier to reason about parallel code (like sequential code)
- Easier to test parallel code (one output per input)
- No subtle parallelism bugs (races, deadlocks)
- Simpler bug detection and debugging

Costs

Focus of today's talk

- Programmer annotation burden
  - *Inferring annotations can help [M. Vakilian et al., ASE 2009]*
- Excludes nondeterministic algorithms by design
  - *We can add nondeterminism with some simple language extensions*
- Expressivity limitations even for deterministic codes
  - *Frameworks etc. can help*

UPCRC Illinois
Universal Parallel Computing Research Center

Why Add Nondeterminism to DPJ?

Nondeterministic algorithms are important

- Several answers are acceptable for given input
- Requiring determinism is unnecessary
- Deterministic schedule may hurt performance

Examples

- Database transactions
- Branch and bound search
- Graph algorithms (clustering, mesh refinement)

Outline

Basic DPJ Language (Review)

Controlling Nondeterminism

New Language Features

Optimizing the Implementation

Evaluation

Conclusion

Overview of DPJ

Programmer

- Partitions object fields into *regions*
- Writes *effect summaries* on methods
- Uses **`cobegin`** and **`foreach`** to specify fork-join parallelism
  - **`cobegin`**: Parallel statements
  - **`foreach`**: Parallel loop iterations

Compiler

- Checks correctness of effects summaries
- Checks noninterference of parallel tasks

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 */
    }
  }
}
```

Pair		
Pair.Fst	fst	3
Pair.Snd	snd	42

Declaring and using region names

UPCRC Illinois
Universal Parallel Computing Research Center

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 */
    }
  }
}
```

Object fields go in regions

Pair		
Pair.Fst	fst	3
Pair.Snd	snd	42

Declaring and using region names

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 */
    }
  }
}
```

Pair		
Pair.Fst	fst	3
Pair.Snd	snd	42

Writing method effect summaries

UPCRC Illinois
Universal Parallel Computing Research Center

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 */
    }
  }
}
```

Effect summaries state method effects

Pair		
Pair.Fst	fst	3
Pair.Snd	snd	42

Writing method effect summaries

UPCRC Illinois
Universal Parallel Computing Research Center

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 */
    }
  }
}
```

Pair		
Pair.Fst	fst	3
Pair.Snd	snd	42

Expressing parallelism

UPCRC Illinois
Universal Parallel Computing Research Center

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 */
    }
  }
}
```

Pair		
Pair.Fst	fst	3
Pair.Snd	snd	42

Compiler uses effects to check noninterference

Expressing parallelism

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 */
    }
  }
}
```

Region Parameters

Class is parameterized by region **P**

```
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 */
    }
  }
}
```

UPCRC Illinois
Universal Parallel Computing Research Center

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 */
    }
  }
}
```

Class is parameterized by region P

Field data resides in P

UPCRC Illinois
Universal Parallel Computing Research Center

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 */
    }
  }
}
```

Class is parameterized by region `P`

Field `data` resides in `P`

Classes are instantiated to types with regions

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 */
    }
  }
}
```

Class is parameterized by region `P`

Field `data` resides in `P`

Classes are instantiated to types with regions

Types provide actual regions for computing effects

UPCRC Illinois
Universal Parallel Computing Research Center

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 */
    }
  }
}
```

Class is parameterized by region P

Field data resides in P

Classes are instantiated to types with regions

Types provide actual regions for computing effects

Distinguish different object instances

UPCRC Illinois
Universal Parallel Computing Research Center

More Realistic Patterns

Support for several important patterns

- Parallel updates through arrays of disjoint references
- Divide and conquer updates
  - Linked trees of arbitrary depth
  - Recursively partitioned arrays
- Commutative operations on concurrent data structures

New type and effect mechanisms

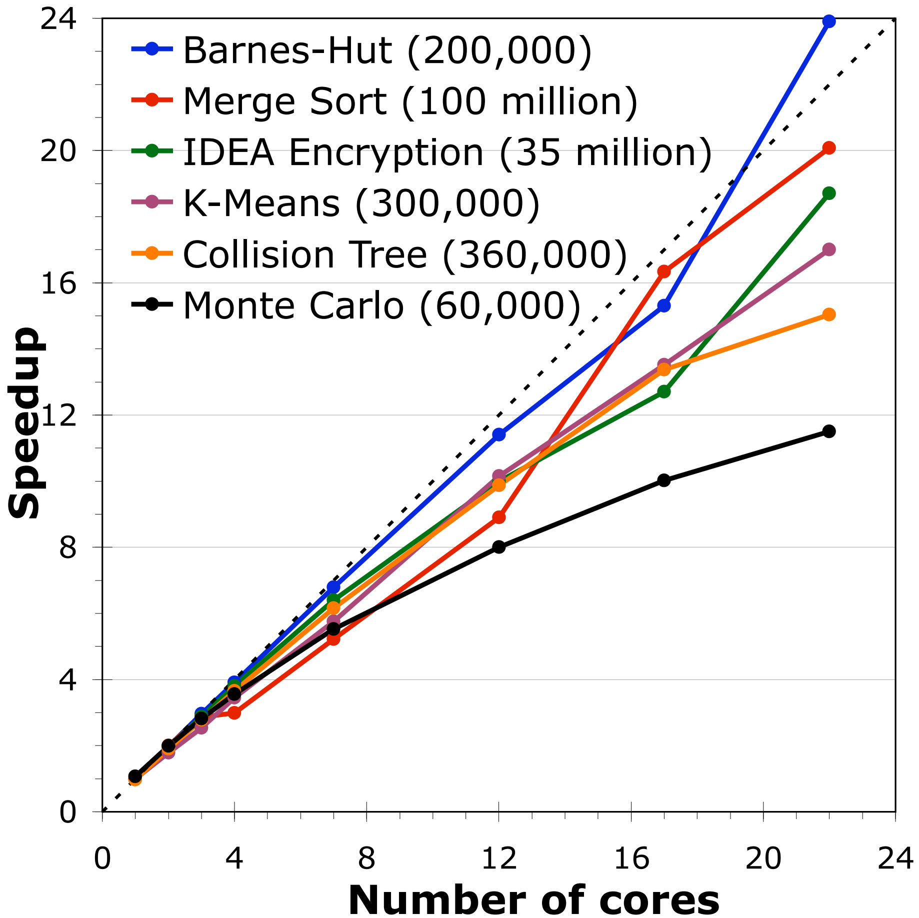
- See OOPSLA 2009 paper for details

Good performance on several realistic benchmarks

- Zero runtime overhead (checking done by compiler)
- But some limitations in expressivity

UPCRC Illinois
Universal Parallel Computing Research Center

Performance Results



- 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

UPCRC Illinois
Universal Parallel Computing Research Center

Outline

Basic DPJ Language (Review)

Controlling Nondeterminism

New Language Features

Optimizing the Implementation

Evaluation

Conclusion

Controlling Nondeterminism

Adding nondeterminsm doesn’t mean all bets are off!

- Don’t revert to low-level synchronization
  - E.g., locks or CAS
  - Brittle, not composable, hard to reason about
- Don’t revert to wild shared memory, races, etc.

Still want strong compile-time guarantees

What Guarantees Should Exist?

Determinism by default

- Program is deterministic *unless* nondeterminism explicitly requested

Strong isolation (atomicity)

- Programmer can identify sections of code to run as if in isolation
- Isolation is *strong*, i.e., no conflicts with *any other code*

Race freedom

- I.e., no *unsynchronized* conflicting accesses (`volatile` OK)
- These kill the semantics under the Java memory model

What Guarantees Should Exist?

Determinism by default

- Program is deterministic *unless* nondeterminism explicitly requested

Strong isolation (atomicity)

- Programmer can identify sections of code to run as if in isolation
- Isolation is *strong*, i.e., no conflicts with *any other code*

Race freedom

- I.e., no *unsynchronized* conflicting accesses (`volatile` OK)
- These kill the semantics under the Java memory model

Ordinary threads programming provides none of these guarantees

UPCRC Illinois
Universal Parallel Computing Research Center

Our Approach

Use software transactional memory (STM)

- Obvious choice for providing isolation guarantee
- Not an *essential* choice, though a robust one
  - Could use automated locking strategies for some patterns
  - Research is not as mature
- Does carry scalar performance penalty

Our contribution: Leverage and extend the type system

- Get *much stronger guarantees* than with STM alone
  - Determinism by default
  - Strong isolation
  - Race freedom
- Eliminate unnecessary STM synchronization

UPCRC Illinois
Universal Parallel Computing Research Center

Our Approach

Use software transactional memory (STM)

- Obvious choice for providing isolation guarantee
- Not an *essential* choice, though a robust one
  - Could use automated locking strategies for some patterns
  - Research is not as mature
- Does carry scalar performance penalty

Our contribution: Leverage and extend the type system

- Get *much stronger guarantees* than with STM alone
  - Determinism by default
  - Strong isolation
  - Race freedom

  STM does not provide at all
- Eliminate unnecessary STM synchronization

UPCRC Illinois
Universal Parallel Computing Research Center

Our Approach

Use software transactional memory (STM)

- Obvious choice for providing isolation guarantee
- Not an *essential* choice, though a robust one
  - Could use automated locking strategies for some patterns
  - Research is not as mature
- Does carry scalar performance penalty

***Our contribution*: Leverage and extend the type system**

- Get *much stronger guarantees* than with STM alone
  - Determinism by default
  - Strong isolation
  - Race freedom
- Eliminate unnecessary STM synchronization

Our Approach

Use software transactional memory (STM)

- Obvious choice for providing isolation guarantee
- Not an *essential* choice, though a robust one
  - Could use automated locking strategies for some patterns
  - Research is not as mature
- Does carry scalar performance penalty

Our contribution: Leverage and extend the type system

- Get *much stronger guarantees* than with STM alone
  - Determinism by default
  - Strong isolation
  - Race freedom
- Eliminate unnecessary STM synchronization

STM provides only weak isolation. Semantics is strange for common patterns.

UPCRC Illinois
Universal Parallel Computing Research Center

Outline

Basic DPJ Language (Review)

Controlling Nondeterminism

New Language Features

Optimizing the Implementation

Evaluation

Conclusion

Summary of Language Features

Expressing nondeterministic parallelism

- `foreach_nd (int i in 0, n)`: Parallel loop
- `cobegin_nd { S1; ...; Sn}`: Parallel statements

Expressing isolation

- Atomic statement (`atomic S`) executes statement `S` in isolation

```
cobegin_nd {
  atomic { x = 0; y = x; };
  atomic x = 1;
}
```

`y == 1`

Effect system

- ***Atomic effects*** keep track of effects done in atomic statements
- Compiler uses effects to enforce guarantees

Summary of Language Features

Expressing nondeterministic parallelism

- `foreach_nd (int i in 0, n)`: Parallel loop
- `cobegin_nd { S1; ...; Sn}`: Parallel statements

Expressing isolation

- Atomic statement (`atomic S`) executes statement `S` in isolation

```
cobegin_nd {
  atomic { x = 0; y = x; };
  atomic x = 1;
}
```

~~`y == 1`~~

Effect system

- ***Atomic effects*** keep track of effects done in atomic statements
- Compiler uses effects to enforce guarantees

Semantics of `cobegin_nd`

Atomic statements generate atomic effects

- `atomic { x = 5; y = 2; } // writes atomic Rx, atomic Ry`

Only atomic effects may interfere

```
cobegin_nd {
    atomic { x = 0; y = 0; };
    atomic { x = 1; y = 1; };
}
```

OK

```
cobegin_nd {
    { x = 0; y = 0; };
    { x = 1; y = 1; };
}
```

Error

Semantics of `cobegin_nd`

Atomic statements generate atomic effects

- `atomic { x = 5; y = 2; } // writes atomic Rx, atomic Ry`

Only atomic effects may interfere

```
cobegin_nd {
    atomic { x = 0; y = 0; };
    atomic { x = 1; y = 1; };
}
```

OK

```
cobegin_nd {
    { x = 0; y = 0; };
    { x = 1; y = 1; };
}
```

Error

These rules guarantee strong isolation and race freedom

Semantics of Effect Summaries

Ordinary effects cover atomic effects...

- `void f() writes Rx { atomic x = 5; } // OK`

...But not vice versa...

- `void f() writes atomic Rx { x = 5; } // Error`

...So we can do sound analysis of method invocations

```
cobegin_nd {
    f();
    g();
}
```

Semantics of Effect Summaries

Ordinary effects cover atomic effects...

- `void f() writes Rx { atomic x = 5; } // OK`

...But not vice versa...

- `void f() writes atomic Rx { x = 5; } // Error`

...So we can do sound analysis of method invocations

```
cobegin_nd {
    f();
    g();
}
```

Atomic effects here mean operations occurred in transactions

Semantics of `cobegin`

Atomic effects "disappear" in branches of `cobegin`

```
cobegin {
    atomic { x = 0 }; // writes Rx, not writes atomic Rx
    atomic { y = 1 }; // writes Ry, not writes atomic Ry
}
```

So `cobegin` still has deterministic semantics:

```
cobegin {
    atomic x = 0;
    atomic x = 1;
}
```

Error

```
cobegin_nd {
    cobegin { atomic x = 0; atomic y = 0 };
    cobegin { atomic x = 1; atomic y = 1 };
}
```

Error

UPCRC Illinois
Universal Parallel Computing Research Center

Semantics of `cobegin`

Atomic effects "disappear" in branches of `cobegin`

```
cobegin {
    atomic { x = 0 }; // writes Rx, not writes atomic Rx
    atomic { y = 1 }; // writes Ry, not writes atomic Ry
}
```

So `cobegin` still has deterministic semantics:

```
cobegin {
    atomic x = 0;
    atomic x = 1;
}
```

Error

```
cobegin_nd {
    cobegin { atomic x = 0; atomic y = 0 };
    cobegin { atomic x = 1; atomic y = 1 };
}
```

Error

These rules guarantee determinism by default

UPCRC Illinois
Universal Parallel Computing Research Center

Reasoning About Programs

Strong isolation and race freedom

- Programmer can think of execution as set of isolated code chunks
  - Sequential code sections
  - `cobegin`, `foreach` branches
  - `atomic` statements inside an `_nd`
  - Sequences between `atomic` statements inside an `_nd`
- Chunks occur in program order

Determinism by default

- If an isolated section contains no `_nd`, it is input-output deterministic
- This is true even inside an `_nd`

UPCRC Illinois
Universal Parallel Computing Research Center

Outline

Basic DPJ Language (Review)

Controlling Nondeterminism

New Language Features

Optimizing the Implementation

Evaluation

Conclusion

UPCRC Illinois
Universal Parallel Computing Research Center

Naive STMs Over-Synchronize

```
class C {
  region rx, ry;
  int x in rx, y in ry;
  void m1() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 0; }
  }
  void m2() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

UPCRC Illinois
Universal Parallel Computing
Research Center

Naive STMs Over-Synchronize

No synchronization needed

```
class C {
  region rx, ry;
  int x in rx, y in ry;
  void m1() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 0; }
  }
  void m2() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

UPCRC Illinois
Universal Parallel Computing Research Center

Need Global Info About Uses

```
class C {
  region rx, ry;
  int x in rx, y in ry;
  void m1() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 0; }
  }
  void m2() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

UPCRC Illinois
Universal Parallel Computing Research Center

Need Global Info About Uses

```
class C {
  region rx, ry;
  int x in rx, y in ry;



  void m2() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

UPCRC Illinois
Universal Parallel Computing Research Center

Need Global Info About Uses

```
class C {
  region rx, ry;
  int x in rx, y in ry;
  void m1() writes atomic rx writes atomic ry {
    atomic { x = 0; y = 0; }
  }
  void m2() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

Need Global Info About Uses

Now synch is needed

```
class C {
  region rx, ry;
  int x in rx, y in ry;
  void m1() writes atomic rx writes atomic ry {
    atomic { x = 0; y = 0; }
  }
  void m2() reads atomic rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

Type System Extensions

```
class C {
  region rx, atomic ry;
  int x in rx, y in ry;
  void m1() reads rx writes atomic ry {
    atomic { int z = x; y = 0; }
  }
  void m2() reads rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

Type System Extensions

Region **ry** is declared atomic

```
class C {
  region rx, atomic ry;
  int x in rx, y in ry;
  void m1() reads rx writes atomic ry {
    atomic { int z = x; y = 0; }
  }
  void m2() reads rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

Type System Extensions

```
class C {
  region rx, atomic ry;
  int x in rx, y in ry;
  void m1() reads rx writes atomic ry {
    atomic { int z = x; y = 0; }
  }
  void m2() reads rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

Region **ry** is declared atomic

Region **rx** is not declared atomic; effect is **reads rx**

Type System Extensions

```
class C {
  region rx, atomic ry;
  int x in rx, y in ry;
  void m1() reads rx writes atomic ry {
    atomic { int z = x; y = 0; }
  }
  void m2() reads rx writes atomic ry {
    atomic { int z = x; y = 1; }
  }
  void m3() {
    cobegin_nd { m1(); m2; }
  }
}
```

Region `ry` is declared atomic

Region `rx` is not declared atomic; effect is `reads rx`

Interfering effects on `rx` would be caught here

UPCRC Illinois
Universal Parallel Computing Research Center

Implementation

Read of non-atomic region gets no barrier (normal read)

Write of non-atomic region gets a *log-only* barrier

- Don't need synchronization (no concurrent access)
- But enclosing transaction may still be aborted
  - Have to record old value in undo log, for restore on abort

Future work

- No log-only barrier if object thrown away on abort
- Common pattern for objects created inside transactions

Outline

Basic DPJ Language (Review)

Controlling Nondeterminism

New Language Features

Optimizing the Implementation

Evaluation

Conclusion

Formal Language and Correctness

Syntax and semantics are done

- Syntax and static semantics for formal core language
- Small-step operational semantics captures interleavings

Soundness proofs are in development

- Assume serializability of atomic sections (STM gives us this)
- Show that type system gives the three properties
  - Input-output determinism for code that contains no **_nd**
  - Strong isolation
  - Race freedom

UPCRC Illinois
Universal Parallel Computing Research Center

Experiments

Benchmarks

- Traveling Salesman Problem (branch and bound search)
- Delaunay mesh refinement (graph algorithm)
- OO7 (synthesized database queries)

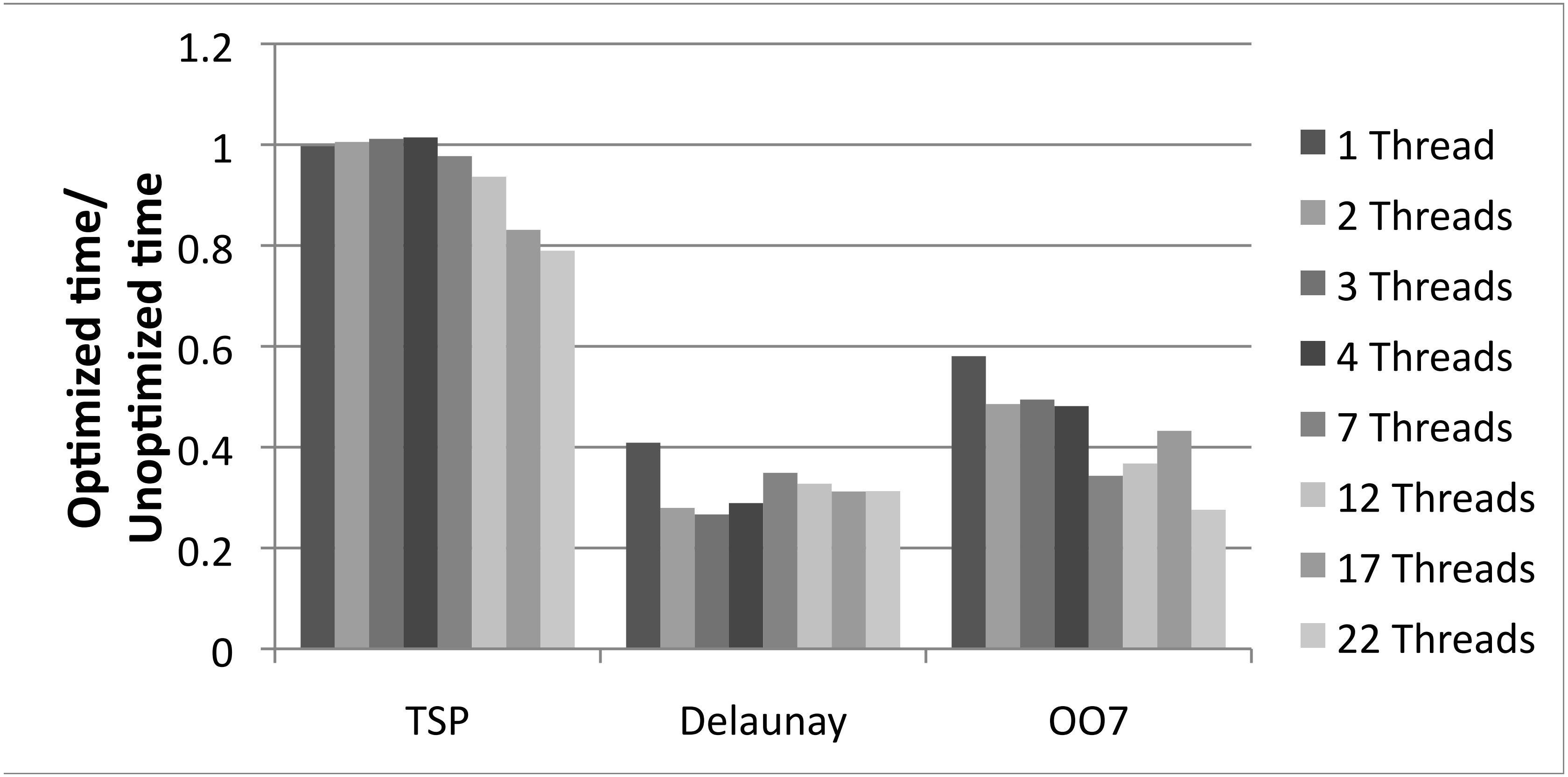
Expressivity

- We can express all three codes in a natural way

Performance

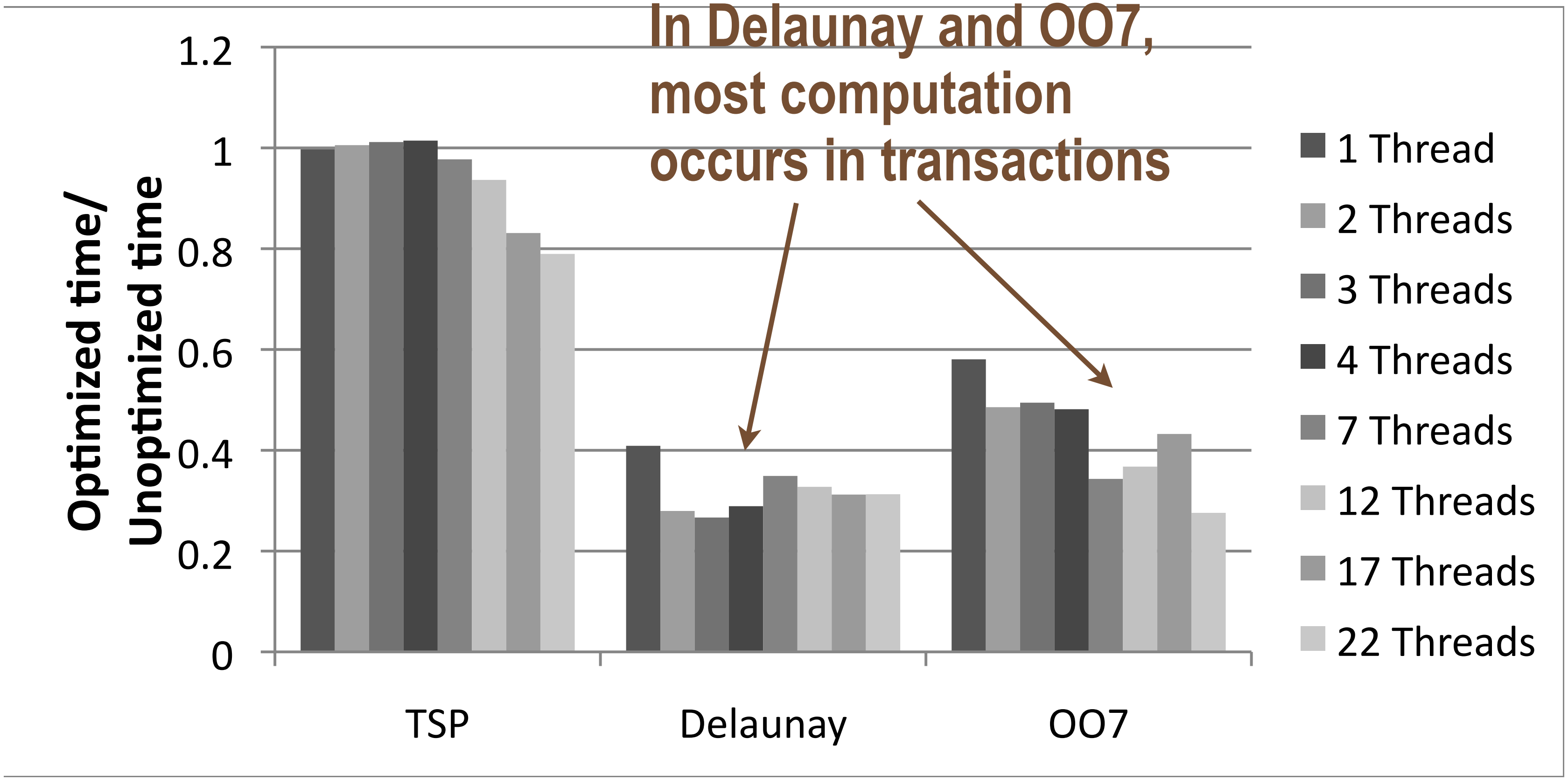
- No extra overhead from standard STM implementation
- Benefits from barrier elimination

Barrier Elimination Results



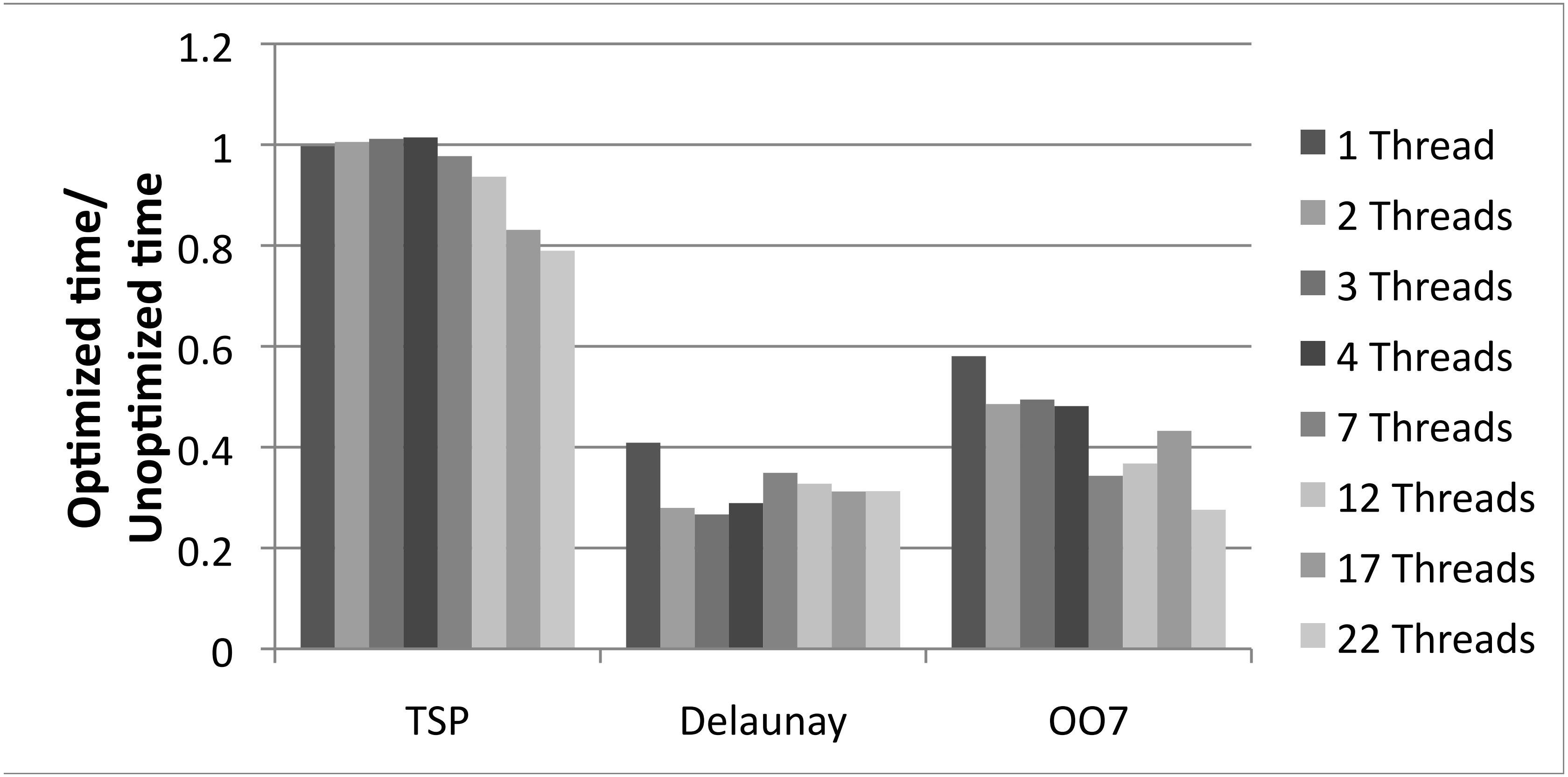
UPCRC Illinois
Universal Parallel Computing Research Center

Barrier Elimination Results



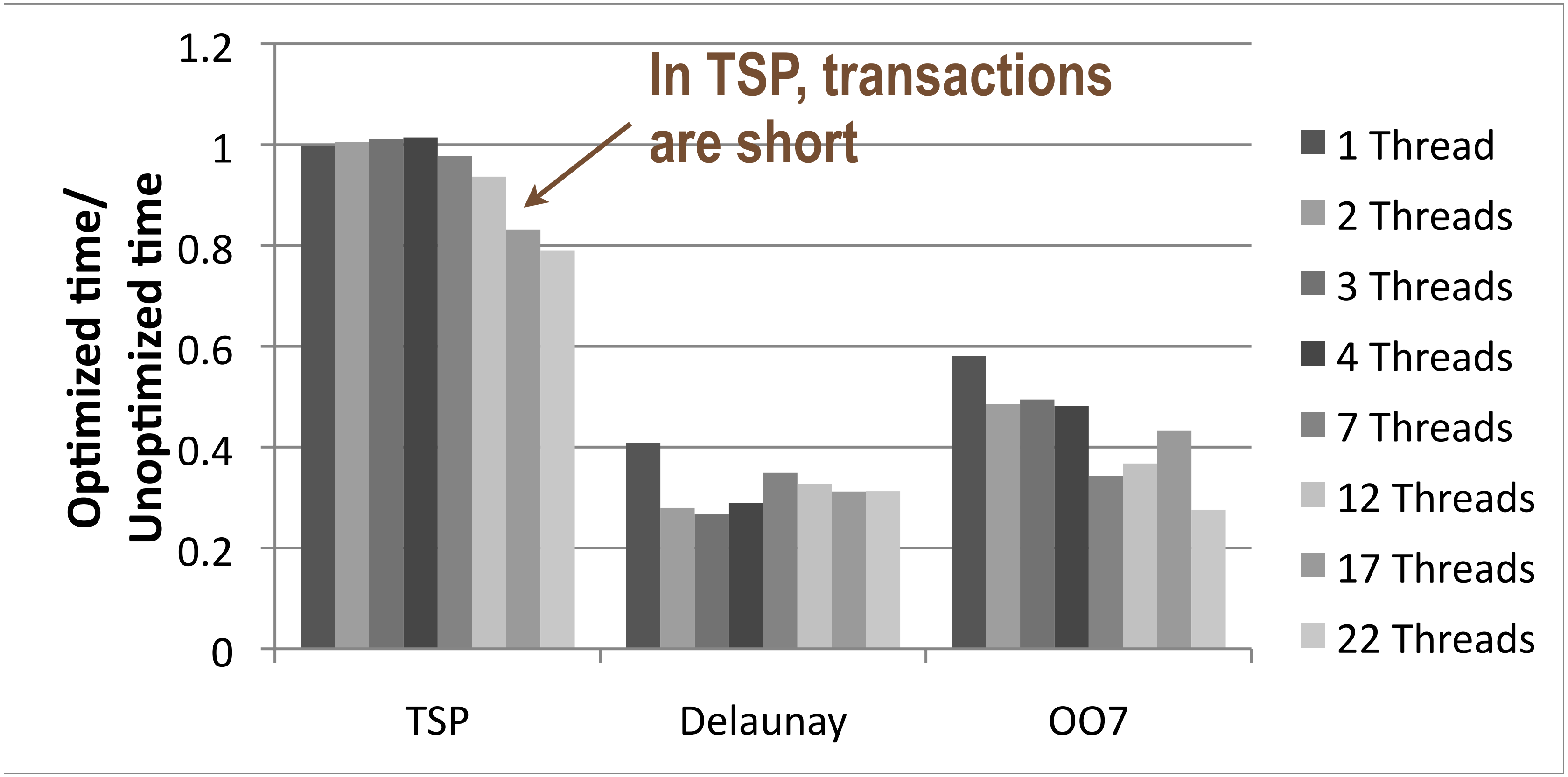
UPCRC Illinois
Universal Parallel Computing Research Center

Barrier Elimination Results



UPCRC Illinois
Universal Parallel Computing Research Center

Barrier Elimination Results



UPCRC Illinois
Universal Parallel Computing Research Center

Conclusion

Basic DPJ *[OOPSLA 2009]*

- Supports deterministic codes with noninterfering parallelism
- Gives good performance, strong guarantee for realistic codes
- Some limitations in expressivity, programmer burden

Support for nondeterministic computations

- New language constructs: `atomic`, `_nd`, atomic effects
- Strong safety guarantees
- Improved performance from barrier elimination