

Interruptible Iterators

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Iteration Abstractions

Important to support iteration abstractions well

- ▶ Clients get on-demand access to elements of a lazily-evaluated sequence
- ▶ Many mainstream languages support IAs
 - ▶ e.g., C++, Python, Ruby
 - ▶ Evolving to support better: C# 2.0, Java 1.5
 - ▶ Libraries too: Java Collections, Microsoft .NET
- ▶ Iterators are hard to implement
 - ▶ Especially if they support imperative update

Interruptible iterators make IAs easier to implement

- ▶ Implemented as part of JMatch

Iterators: Easy to Use, Hard to Write

Easy to use: Java iterator interface

```
interface Iterator {  
    boolean hasNext(); // Is there a next element?  
    Object next(); // Return the next element  
    void remove(); // Remove last element returned  
}
```

Can be hard to implement

- ▶ Iteration must continue where it last left off
- ▶ Iterator can become awkward state machine

Binary Tree Iterator Example in Java

```
class TreeIterator implements Iterator {
    Iterator subIterator;
    boolean hasNext;
    Object current;

    // 1 = Iterating through left child
    // 2 = Just yielded current node value
    // 3 = Iterating through right child
    int state;

    TreeIterator() {
        subIterator = Tree.this.left.iterator();
        state = 1;
        current = preload();
    }

    public boolean hasNext() {
        return hasNext;
    }

    public Object next() {
        if (!hasNext)
            throw new NoSuchElementException();

        Object result = current;
        current = preload();
        return result;
    }
}
```

```
private Object preload() {
    loop: while (true) {
        switch (state) {
            case 1:
            case 3:
                hasNext = true;

                if (subIterator.hasNext()) {
                    return subIterator.next();
                }

                if (state == 1) {
                    state = 2;
                    return Tree.this.value;
                }

                hasNext = false;
                return null;

            case 2:
                subIterator =
                    Tree.this.right.iterator();
                state = 3;
                continue loop;
            }
        }
    }
}
```

Binary Tree Iterator Example in Java

```
class TreeIterator implements Iterator {
    Iterator subIterator;
    boolean hasNext;
    Object current;

    // 1 = Iterating through left child
    // 2 = Just yielded current node value
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    int state;

    TreeIterator() {
        subIterator = Tree.this.left.iterator();
        state = 1;
        current = preload();
    }

    public boolean hasNext() {
        return hasNext;
    }

    public Object next() {
        if (!hasNext)
            throw new NoSuchElementException();

        Object result = current;
        current = preload();
        return result;
    }
}
```

```
private Object preload() {
    loop: while (true) {
        switch (state) {
            case 1:
            case 3:
                hasNext = true;

                if (subIterator.hasNext()) {
                    return subIterator.next();
                }

                if (state == 1) {
                    subIterator = Tree.this.left.iterator();
                    state = 2;
                } else {
                    subIterator = Tree.this.right.iterator();
                    state = 3;
                    continue loop;
                }
            }
        }
    }
}
```

Even worse when you
add support for updates

Coroutine Iterators

- ▶ Increasingly popular: C# 2.0, Python, Ruby
- ▶ Iterator as a coroutine:
 - ▶ Separate stack
 - ▶ Iterator suspends execution by *yielding* values
 - ▶ Client obtains more values by resuming iterator

Example: JMatch binary tree iterator

```
class Node {
  int val; Node left, right;
  int elements() iterates(result) {
    foreach (int elt = left.elements()) yield elt;
    yield val;
    foreach (int elt = right.elements()) yield elt;
  }
}
```

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class Node {  
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    int elements() iterates(result) {  
        foreach (int elt = left.elements()) yield elt;  
        yield val;  
        foreach (int elt = right.elements()) yield elt;  
    }  
}
```

elements is an iterator

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Example: JMatch binary tree iterator

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class Node {  
    int val; Node left, right;  
    int elements() iterates(result) {  
▶ foreach (int elt = left.elements()) yield elt;  
    yield val;  
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}
```


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     yield val;
    foreach (int elt = right.elements()) yield elt;
  }
}
```

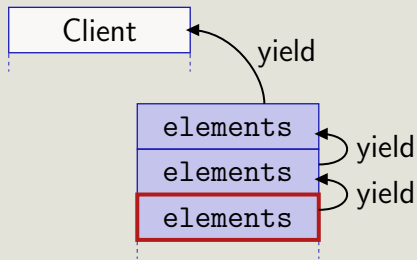
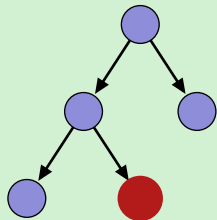
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Example: JMatch binary tree iterator

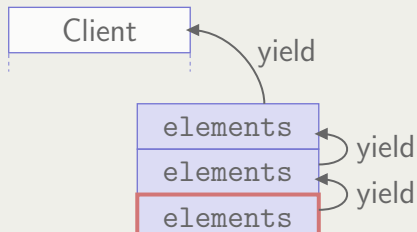
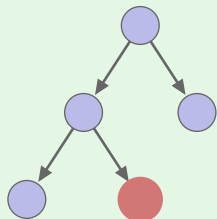
```
class Node {  
    int val; Node left, right;  
    int elements() iterates(result) {  
        foreach (int elt = left.elements()) yield elt;  
        yield val;  
         foreach (int elt = right.elements()) yield elt;  
    }  
}
```

Coroutine Iterators



```
class Node {
  int val; Node left, right;
  int elements() iterates(result) {
    foreach (int elt = left.elements()) yield elt;
    yield val;
    foreach (int elt = right.elements()) yield elt;
  }
}
```

Coroutine Iterators



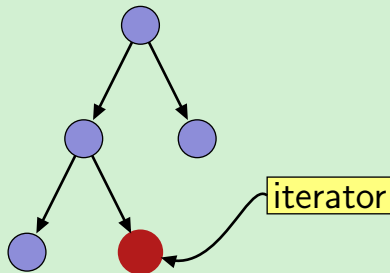
Only a partial solution: no imperative updates

```
class Node {
  int val; Node left, right;
  int elements() iterates(result) {
    foreach (int elt = left.elements()) yield elt;
    yield val;
    foreach (int elt = right.elements()) yield elt;
  }
}
```

Imperative Updates

- ▶ Unsafe to change underlying data structure directly during iteration
- ▶ All updates must go through the iterator
 - ▶ Java: `remove()`
- ▶ Previous coroutine iterators don't have update

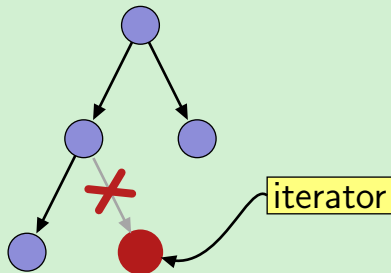
Example: Tree iterator



Imperative Updates

- ▶ Unsafe to change underlying data structure directly during iteration
- ▶ All updates must go through the iterator
 - ▶ Java: `remove()`
- ▶ Previous coroutine iterators don't have update

Example: Tree iterator



Iterator no longer points to part of the tree

Interruptible Iterators

JMatch extends coroutine iterators to handle updates via *interrupts*:

1. Client raises interrupt
2. Iterator handles interrupt
3. Control returns to client after raise

Example

```
Collection c = ...;  
foreach (Object o = c.elements()) {  
    if (o == null) raise new Remove();  
    System.out.println(o);  
}
```

Interruptible Iterators

JMatch extends coroutine iterators to handle updates via *interrupts*:

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Example

```
Collection c = ...;  
foreach (Object o = c.elements()) {  
    if (o == null) raise new Remove();  
    System.out.println(o);  
}
```

Generates a Remove interrupt

Interruptible Iterators

JMatch extends coroutine iterators to handle updates via *interrupts*:

1. Client raises interrupt
2. Iterator handles interrupt
3. Control returns to client after raise

Example

Receives and handles the interrupt

```
Collection c = ...;
foreach (Object o = c.elements()) {
    if (o == null) raise new Remove();
    System.out.println(o);
}
```

Interruptible Iterators

JMatch extends coroutine iterators to handle updates via *interrupts*:

1. Client raises interrupt
2. Iterator handles interrupt
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Example

Collection

```
foreach (Object o = c.elements()) {  
    if (o == null) raise new Remove();  
    System.out.println(o);  
}
```

Execution continues immediately after raise statement

Interruptible Iterators

JMatch extends coroutine iterators to handle updates via *interrupts*:

1. Client raises interrupt
2. Iterator handles interrupt
3. Control returns to client after raise

Example

```
Collection c = ...;  
foreach (Object o = c.elements()) {  
    if (o == null) raise new Remove();  
    System.out.println(o);  
}
```

Declaring Interrupt Handlers

- ▶ JMatch iterators declare handled interrupts
- ▶ Compiler checks all interrupts are handled

Example

```
interface Collection {  
    ...  
    Object elements() traps Remove  
                           iterates(result);  
}
```

Declaring Interrupt Handlers

- ▶ JMatch iterators declare handled interrupts
- ▶ Compiler checks all interrupts are handled

Example

```
interface Collection {  
    ...  
    Object elements() traps Remove  
    iterates(result);  
}
```

elements is an iterator that handles Remove interrupts

traps Remove
iterates(result);

Writing an Interruptible Iterator

Example: Linked list iterator

```
// Object head; List tail;
Object elements() traps SetValue iterates(result) {

    yield head;

    foreach (Object elt = tail.elements())
        yield elt;
}
```

Writing an Interruptible Iterator

Example: Linked list iterator

```
// Object head; List tail;
Object elements() traps SetValue iterates(result) {
    yield head;
    foreach (Object elt = tail.elements())
        yield elt;
}
```

Handling SetValue overwrites previous element returned (à la Java: `ListIterator.set()`)

Writing an Interruptible Iterator

Example: Linked list iterator

```
// Object head; List tail;
Object elements() traps SetValue iterates(result) {
    yield head;

    foreach (Object elt = tail.elements())
        yield elt;
}
```

Interrupt appears to be raised by yield; propagates outward like an exception

Writing an Interruptible Iterator

Example: Linked list iterator

```
// Object head; List tail;
Object elements() traps SetValue iterates(result) {
  try {
    yield head;
  } trap (SetValue s) {
    head = s.value; // resume in caller
  }
  foreach (Object elt = tail.elements())
    yield elt;
}
```

Writing an Interruptible Iterator

Example: Linked list iterator

```
// Object head; List tail;
Object elements() traps SetValue iterates(result) {
  try {
    yield head;
  } trap (SetValue s) {
    head = s.value; // resume in caller
  }
  foreach (Object elt = tail.elements())
    yield elt;
}
```

Interrupt appears here too

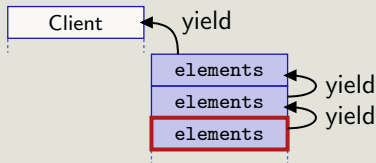
Writing an Interruptible Iterator

Example: Linked list iterator

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// Object head; List tail;
Object elements() traps SetValue iterates(result) {
  try {
    yield head;
  } trap (SetValue s) {
    head = s.value; // resume in caller
  }
  foreach (Object elt = tail.elements())
    yield elt;
}
```

Receives interrupt

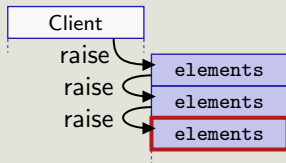
Writing an Interruptible Iterator



Example: Linked list iterator

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  try {
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```

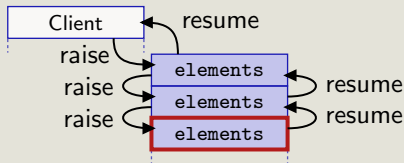
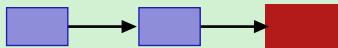
Writing an Interruptible Iterator



Example: Linked list iterator

```
// Object head; List tail;
Object elements() traps SetValue iterates(result) {
  try {
    yield head;
  } trap (SetValue s) {
    head = s.value; // resume in caller
  }
  foreach (Object elt = tail.elements())
    yield elt;
}
```

Writing an Interruptible Iterator



Example: Linked list iterator

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// Object head; List tail;
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  try {
    yield head;
  } trap (SetValue s) {
    head = s.value; // resume in caller
  }
  foreach (Object elt = tail.elements())
    yield elt;
}
```

Declarative Iterators



State Machine
Iterators



Coroutine
Iterators



Declarative
Iterators

+ Interrupts

Declarative Iterators

Example: JMatch hash map [PADL 2003]

```
boolean contains(Object key, Object value)
```

```
    iterates(key,value) iterates(key) returns(value)  
(  
    int n = hash(key) &&  
    Bucket b = table[n] &&  
    b.contains(key, value)  
)
```

Example uses

Declarative Iterators

Example: JMatch hash map [PADL 2003]

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boolean contains(Object key, Object value)
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    iterates(key,value) iterates(key) returns(value)  
(  
    int n = hash(key) &&  
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    b.contains(key, value)  
)
```

Logical formula
interpreted in
multiple ways

Example uses

Declarative Iterators

Example: JMatch hash map [PADL 2003]

```
boolean contains(Object key, Object value)
```

```
iterates(key,value) iterates(key) returns(value)
```

```
(  
  int n = hash(key) &&  
  Bucket b = table[n] &&  
  b.contains(key, value)  
)
```

Mode declarations

Example uses

Declarative Iterators

Example: JMatch hash map [PADL 2003]

```
boolean contains(Object key, Object value)
```

```
iterates(key,value) iterates(key) returns(value)  
(  
  int n = hash(key) &&  
  Bucket b = table[n] &&  
  b.contains(key, value)  
)
```

Iterates all key-value pairs

Example uses

```
foreach (map.contains(Object key, Object value)) ...
```

Declarative Iterators

Example: JMatch hash map [PADL 2003]

```
boolean contains(Object key, Object value)
```

```
    iterates(key, value) iterates(key) returns(value)  
(  
    int n = hash(key) &&  
    Bucket b = table[n] &&  
    b.contains(key, value)  
)
```

Iterates all keys that map to a given value

Example uses

```
foreach (map.contains(Object key, Object value)) ...  
foreach (map.contains(Object key, "foo")) ...
```

Declarative Iterators

Example: JMatch hash map [PADL 2003]

```
boolean contains(Object key, Object value)
```

```
    iterates(key,value) iterates(key) returns(value)  
(  
    int n = hash(key) &&  
    Bucket b = table[n] &&  
    b.contains(key, value)  
)
```

Returns value mapped
by a given key

Example uses

```
foreach (map.contains(Object key, Object value)) ...  
foreach (map.contains(Object key, "foo")) ...  
let map.contains("foo", Object value);
```

Declarative Iterators

Example: JMatch hash map [PADL 2003]

```
boolean contains(Object key, Object value)
```

```
    iterates(key,value) iterates(key) returns(value)  
(  
    int n = hash(key) &&  
    Bucket b = table[n] &&  
    b.contains(key, value)  
)
```

Implicit mode

Example uses

```
foreach (map.contains(Object key, Object value)) ...  
foreach (map.contains(Object key, "foo")) ...  
let map.contains("foo", Object value);  
if (map.contains("foo", "bar")) ...
```

Declarative Iterators + Imperative Update

Example: JMatch hash map [PADL 2003]

```
boolean contains(Object key, Object value)
```

```
traps Remove
```

```
iterates(key, value) iterates(key) returns(value)
```

```
(
```

```
int n = hash(key) &&
```

```
Bucket b = table[n] &&
```

```
b.contains(key, value)
```

```
)
```

Updates can be supported
via interrupts

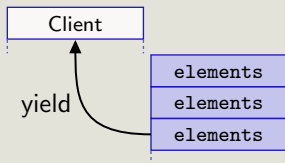
Example use

```
foreach (map.contains(Object key, Object value))
```

```
if (value == null) raise new Remove();
```

Implementation

- ▶ JMatch implemented using Polyglot extensible compiler framework [CC 2003]
 - ▶ Java back-end available for download
 - ▶ Designed C++ back-end for performance evaluation
 - ▶ Better memory management for coroutine stack
- ▶ *Tail-yield optimisation*: send values back to client in constant time



Evaluation

Expressiveness (LOC)

	Java	JMatch	Savings
ArrayList	204	112	45%
LinkedList	249	155	38%
HashMap	434	158	64%
TreeMap	805	472	41%
Total	1692	897	47%

Performance vs. C++ STL

Average 3% difference iterating 250k elements:
LinkedList, HashMap, TreeMap vs. STL equivalent

- ▶ More results in paper, including vs. Java

Related Work

- ▶ Coroutine iterators
 - ▶ CLU, ICON, Python, Ruby, C#
 - ▶ Sather: Limited support for imperative updates through “hot” arguments
- ▶ Coroutines
 - ▶ Simula, Modula-2, BETA
- ▶ Resumption-style exceptions
 - ▶ Cedar
- ▶ First-class continuations
 - ▶ SML/NJ, Scheme, Ruby

Summary

- ▶ Interrupts make it easier to write iteration abstractions with imperative update
 - ▶ Supports coroutine and declarative iterators
- ▶ Implemented for Java in JMatch
- ▶ LOC savings without performance penalty

Also in the paper...

- ▶ Non-compositionality of Java iterators
- ▶ Interaction of interrupts & exceptions
- ▶ Static checking of interrupts
 - ▶ Checks all raised interrupts have unique handler
- ▶ Support for first-class iterator objects
 - ▶ Implement Java iterator interface

<http://www.cs.cornell.edu/projects/jmatch/>

Java Iterators are Non-Compositional

Client 

1	2	3	4	5
---	---	---	---	---

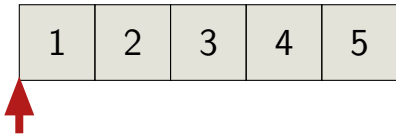
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    void remove();  
}
```

Java Iterators are Non-Compositional

Client



List iterator



```
interface Iterator {  
    boolean hasNext();  
    Object next();  
    void remove();  
}
```

Java Iterators are Non-Compositional

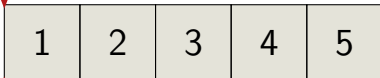
Client



Filtering iterator



List iterator



```
interface Iterator {  
    boolean hasNext();  
    Object next();  
    void remove();  
}
```

Java Iterators are Non-Compositional

Client  `next()`

Filtering iterator



List iterator

```
interface Iterator {  
    boolean hasNext();  
    Object next();  
    void remove();  
}
```

Java Iterators are Non-Compositional

Client



hasNext()

Filtering iterator



List iterator

```
interface Iterator {  
    boolean hasNext();  
    Object next();  
    void remove();  
}
```


Java Iterators are Non-Compositional

Client  !

Filtering iterator



List iterator

```
interface Iterator {  
    boolean hasNext();  
    Object next();  
    void remove();  
}
```

Performance Results

	ArrayList	LinkedList	HashMap	TreeMap
JMatch	135.0	56.1	3.7	3.1
C++ STL	215.0	57.7	3.1	3.9
Java	6.3	10.3	4.2	3.5

Millions of elements iterated per second, iterating over collections of 250k elements. Average of 8 measurements, $\sigma \leq 5\%$.