Interruptible Iterators

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Computer Science

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

```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;
  }
```

```java
  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

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class TreeIterator implements Iterator {
  Iterator subIterator;
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  Object current;

  // 1 = Iterating through left child
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  int state;

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

  public boolean hasNext() {
    return hasNext;
  }

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

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

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

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

                     1) {

                     .this.value;

                     se;
        return null;

      case 2:
        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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}
```

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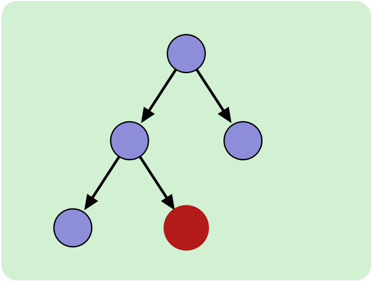
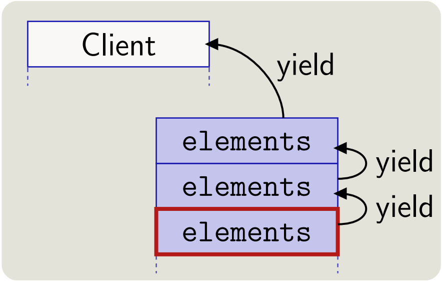
Coroutine Iterators





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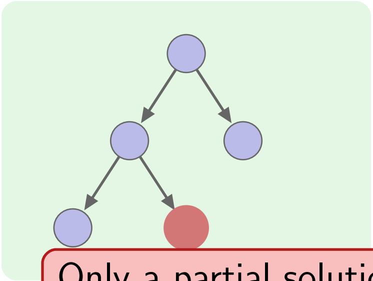
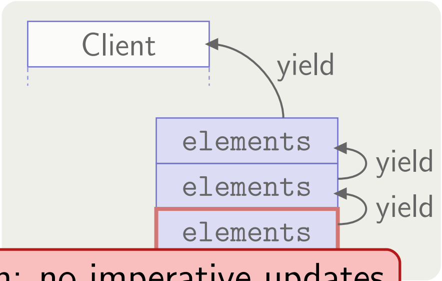
Coroutine Iterators





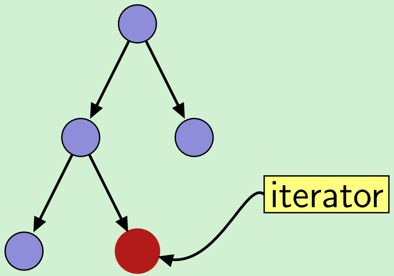
Only a partial solution: no imperative updates

```
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



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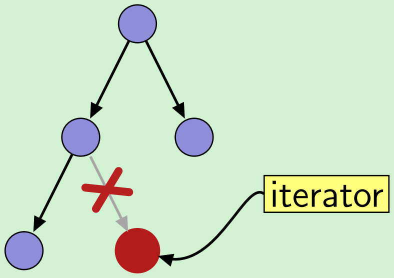

Iterator no longer points to part of the tree

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

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Example

Generates a `Remove` interrupt

```
Collection c = ...;
foreach (Object o = c.elements()) {
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  System.out.println(o);
}
```

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Example

Receives and handles the interrupt

```
Collection c = ...;
foreach (Object o = c.elements()) {
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}
```

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

Execution continues immediately after `raise` statement

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

Interruptible Iterators

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Example

```
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  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

`elements` is an iterator that handles `Remove` interrupts

Example

```
interface Collection {
  ...
  Object elements() 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

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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

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

Interrupt appears here too

Writing an Interruptible Iterator

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  try {
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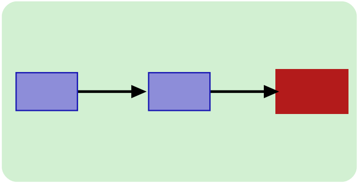
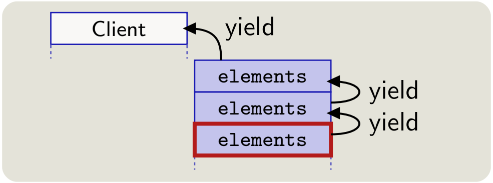
```

Receives interrupt

Writing an Interruptible Iterator





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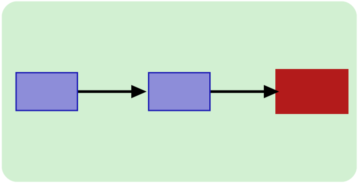
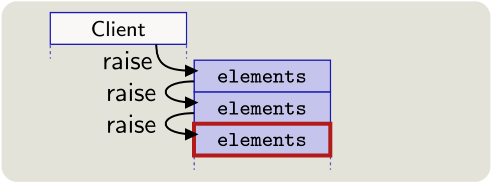
Writing an Interruptible Iterator





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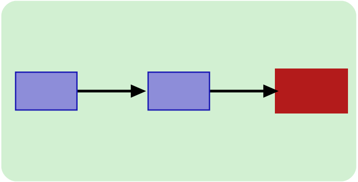
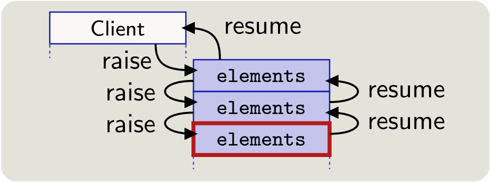
Writing an Interruptible Iterator





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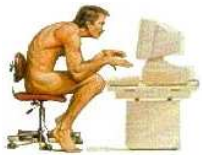
```

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

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

Logical formula interpreted in multiple ways

Example uses

Declarative Iterators

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boolean contains(Object key, Object value)

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

Mode declarations

Example uses

Declarative Iterators

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  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]

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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]

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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]

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

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)
)
```

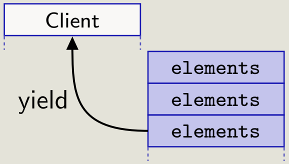
Updates can be supported via interrupts

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

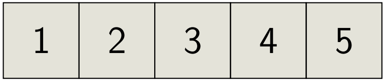
Also in the paper...

- 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



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Java Iterators are Non-Compositional

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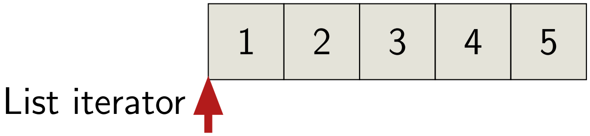

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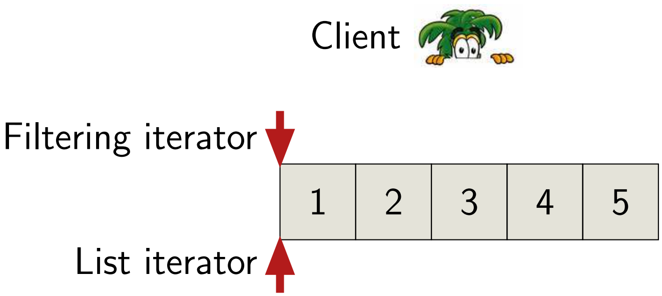

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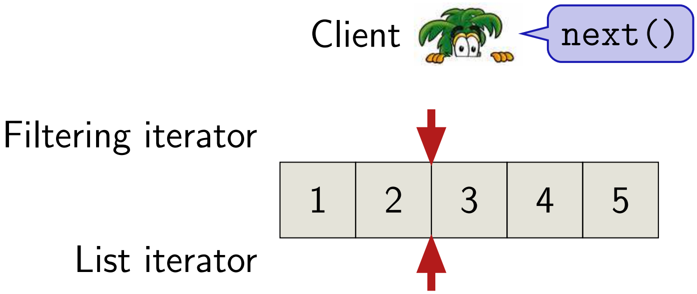

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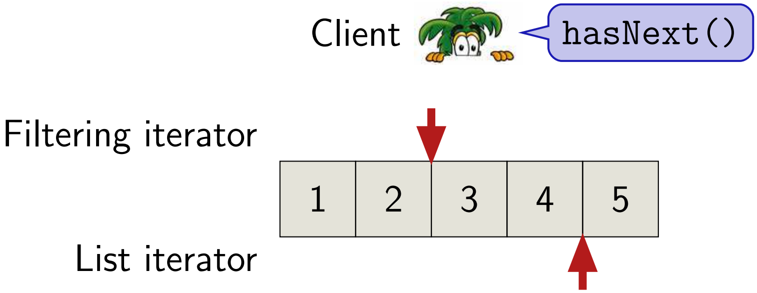

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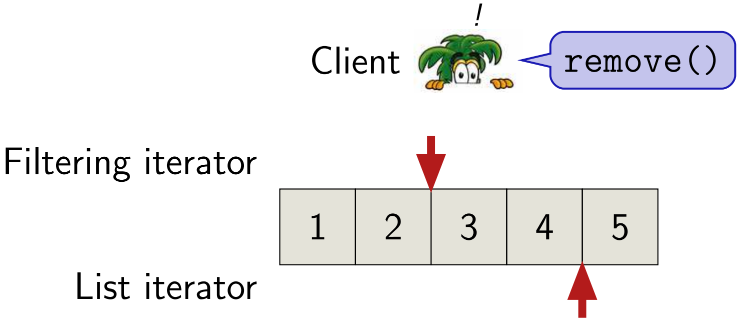

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```

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, $\sigma \leq 5\%$.