CSc 520 — Principles of Programming Languages

31 : Control Structures — Iterators

Christian Collberg
Department of Computer Science
University of Arizona
collberg+520@gmail.com

April 7, 2008

1 Iterators

- `FOR`-loops are typically used to iterate over some range of enumerable values.
- `Iterators` are used to iterate over an **abstraction**, such as the elements of a list, the nodes of a tree, the edges of a graph, etc.
- For example,

```
for n := tree_nodes_in_inorder(T) do
   print n
end
```

Iterators in Java

2 Iterators in Java

- In object-oriented languages it is typical to create an **enumeration object** `i` which contains the current state of the iteration:

```
LinkedList<String> L = new LinkedList<String>();
L.add("Bebe");
L.add("Wendy");
L.add("Nelly");

Iterator<String>  i = L.iterator();
while (i.hasNext()) {
   String c = i.next();
   System.out.println(c);
}
```

- This is not as clean as in languages with built-in support for iterators.

3 Java 1.5 extended `for`-loop

- As of Java 1.5, the `for`-loop has been augmented so you can say

```
LinkedList<String> L = new LinkedList<String>();
L.add("Bebe");
L.add("Wendy");
L.add("Nelly");
for (String c : L)
   System.out.println(c);
```

- However, this is just syntactic sugar for calls to the `Iterator` class.

4 Java 1.5 extended `for`-loop

- You can tell that this is just syntactic sugar by looking at the bytecode the compiler generates (use `javap -c Iter`):

```
29: aload_1
30: invokevirtual #8;       // LinkedList.iterator:
33: astore_2
34: aload_2
35: invokeinterface #9,1;  // java/util/Iterator.hasNext
40: ifeq 63
43: aload_2
44: invokeinterface #10,1; // java/util/Iterator.next
49: checkcast #11;         // java/lang/String
52: astore_3
53: getstatic #12;         // java/lang/System.out
56: aload_3
57: invokevirtual #13;     // java/io/PrintStream.println
60: goto 34
```

Ruby iterators

5 Blocks

- Let's write a simple Ruby for loop to search through an array looking for a particular value:

```
$flock = ["huey","dewey","louie"]

def isDuck?(name)
   for i in 0...$flock.length
      if $flock[i] == name then
         return true
      end
   end
   return false
end

puts isDuck?("dewey"), isDuck?("donald")
```

6 Iterators

- Ruby's *iterators* are an easier way to do this.
- The `Array` class implements a method `find` that iterates through the array.

```
def isDuck?(name)
   $flock.find do |x|
      x == name
   end
end

puts isDuck?("dewey")
puts isDuck?("donald")
```

7 Yield

- A block is enclosed within { } or `do...end`. Arguments to the block (there can be more than one) are given within `|...|`.
- A block is passed to a method by giving it after the list of "normal" parameters.
- The method invokes the block by using `yield`.
- `yield` can take an argument which the method passed back to the block.

8 Yield...

```
def triplets()
   yield "huey"
   yield "dewey"
   yield "louie"
end

triplets() {|d| puts d}

triplets() do |d|
  puts d
end
```

9 Factorial

- Here's the factorial function, as an iterator.

```
def fac(n)
   f = 1
   for i in 1..n
     f *= i
     yield f
   end
end

fac(5) {|f| puts f}
```

10 Passing arguments

- `yield` can pass more than one value to the block.

```
def fac(n)
   f = 1
   for i in 1..n
     f *= i
     yield i,f
   end
end

fac(5) do |i,x|
   puts "#{i}! = #{x}"
end
```

11 Nesting iterators

- Iterators can be nested.

```
fac(3) do |i,x|
   fac(3) do |j,y|
      puts "#{i}! * #{j}! = #{x*y}"
```

```
   end
end
```

12 Scope

- A local variable which is active when the block is started up, can be accessed (and modified) within the block.

```
def sumfac(n)
   y = 0
   fac(n) do |i,x|
      y = y + x
   end
   return y
end

puts sumfac(5)
```

13 Implementing `Array#find`

- We can implement our own `find` method:

```
def find(arr)
   for i in 0..arr.length
      if yield arr[i] then return true end
   end
   return false
end

puts find($flock) {|x| x=="dewey"}
puts find($flock) {|x| x=="donald"}
```

14 `Array#collect`

- `collect` applies the block to every element of an array, creating a new array. This is similar to Haskell's `map`.

```
$flock = ["huey","dewey","louie"]
$flock.each {|x| puts x}

puts $flock.collect {|x| x.length}
puts $flock.collect do |x|
   "junior woodchuck, General " + x
end
```

15 `Array#inject`

- `inject(init)` is similar to Haskell's `foldl`.
- `inject()` without an argument is like Haskell's `foldl1`, i.e. it uses the first element of the array as the starting value.

```
x = $flock.inject("") do |elmt,total|
   total = elmt + " " + total
end
puts x

x = $flock.inject() do |elmt,total|
   total = elmt + " " + total
end
puts x
```

Icon Generators

16 Icon Generators

Procedures are really generators; they can return 0, 1, or a sequence of results. There are three cases

`fail` The procedure fails and generates no value.

`return e` The procedure generates one value, `e`.

`suspend e` The procedure generates the value `e`, and makes itself ready to possibly generate more values.

```
procedure To(i,j)
   while i <= j do {
      suspend i
      i+:= 1
   }
end
```

17 Example

```
procedure To(i,j)
   while i <= j do {
      suspend i
      i+:= 1
   }
end

procedure main()
   every k := To(1,3) do
      write(k)
end
```

18 simple.icn

```
procedure P()
   suspend 3
   suspend 4
   suspend 5
end

procedure main()
   every k := P() do
      write(k)
end
```

19 simple.icn. . .

```
> setenv TRACE 100
> simple
             :       main()
simple.icn   :    8  | P()
simple.icn   :    2  | P suspended 3
3
simple.icn   :    9  | P resumed
simple.icn   :    3  | P suspended 4
4
simple.icn   :    9  | P resumed
simple.icn   :    4  | P suspended 5
5
simple.icn   :    9  | P resumed
simple.icn   :    5  | P failed
simple.icn   :   10  main failed
```

Iterators in CLU

20 CLU-Style Iterators

- Iterators were pioneered by CLU, a (dead) class-based language from MIT.

```
setsum = proc(s:intset) returns(int)
   sum :  int := 0
   for e:int in intset$elmts(s) do
      sum := sum + e
   end
   return sum
end setsum
```

21 CLU-style Iterators...

- Procedure `setsum` computes the sum of the elements in a set of integers.
- `setsum` iterates over an instance of the abstract type `intset` using the `intset$elmts` iterator.
- Each time around the loop, `intset$elmts` yields a new element, suspends itself, and returns control to the loop body.

22 CLU-style Iterators...

```
intset = cluster is create,elmts,...
   rep = array[int]
   elmts = iter(s:cvt) yields(int)
      i :  int := rep$low(s)
      while i <= rep$high(s) do
         yield (s[i])
         i = i + 1
      end
   end elmts
end intset
```

23 CLU-style Iterators...

- A CLU `cluster` is a typed module; a C++ class, but without inheritance.
- CLU makes a clear distinction between the abstract type (the cluster as seen from the outside), and its representation (the cluster from the inside). The **rep** clause defines the relationship between the two.

24 CLU-style Iterators. . .

```
   elmts = iter(s:cvt) yields(int)
      i : int := rep$low(s)
      while i <= rep$high(s) do
         yield (s[i])
         i = i + 1
      end
   end elmts
```

25 CLU-style Iterators. . .

- **s:cvt** says that the operation converts its argument from the abstract to the representation type.
- `rep$low` and `rep$high` are the bounds of the array representation.
- `yield` returns the next element of the set, and then suspends the iterator until the next iteration.
- Iterators may be nested and recursive.

26 CLU-style Iterators. . .

```
array = cluster [t: type] is ...
   elmts = iter(s:array[t]) yields(t)
      for i:int in int$from_to(
            array[t]$low(a),
            array[t]$high(a)) do
         yield (a[i])
      end
   end elmts
end array
elmts = iter(s:cvt) yields(int)
   for i:int in array$elmts(s) do
      yield (i)
   end
end elmts
```

27 CLU-style Iterators. . .

- Iterators may invoke other iterators.
- CLU supports constrained generic clusters (like Ada's generic packages, only better).

28 CLU Iterators — Example A

- Here's an example of a CLU iterator that generates all the integers in a range:

```
for i in from_to_by(first,last,step) do
   ...
end
```

29 CLU Iterators — Example A...

```
from_to_by = iter(from,to,by:int) yields(int)
   i : int := from
   if by> 0 then
      while i <= to do
         yield i
         i +:= by
      end
   else
      while i >= to do
         yield i
         i +:= by
      end
   end
```

30 CLU Iterators — Example B

- Here's an example of a CLU iterator that generates all the binary trees of n nodes.

```
for t: bin_tree in bin_tree$tree_gen(n) do
   bin_tree$print(t)
end
```

31 CLU Iterators — Example B...

```
bin_tree = cluster ...
   node = record [left,right : bin_tree]
   rep  = variant [some : node, empty : null]
   ...
   tree_gen = iter (k : int) yields (cvt)
      if k=0 then
         yield red$make_empty(nil)
      else
         for i:int in from_to(1,k) do
            for l : bin_tree in tree_gen(i-1) do
              for r : bin_tree in tree_gen(k-i) do
                 yield rep$make_some(node${l,r})
              end
            end
      end
   end tree_gen
   ...
end
```

Implementing Iterators

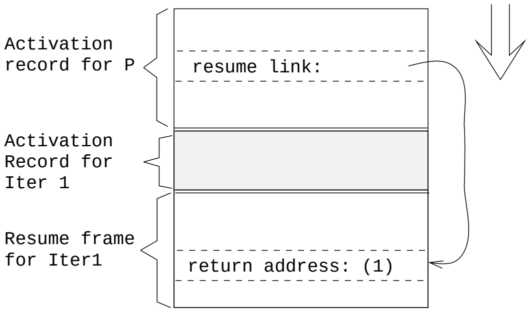
32 Iterator Implementation

```
Iter1 = iter ( ...  )
  ...  yield x
  (1) ...
  end
end Iter1
P = proc ( ...  )
  for i in Iter1(...)  do
    S
  end
end P
```

33 Iterator Implementation

- Calling an iterator is the same as calling a procedure. Arguments are transferred, an activation record is constructed, etc.
- Returning from an iterator is also the same as returning from a procedure call.

34 Iterator Implementation...



35 Iterator Implementation...

- When an iterator yields an item, its activation record remains on the stack. A new activation record (called a **resume frame**) is added to the stack.
- The resume frame contains information on how to resume the iterator. The **return address**-entry in the resume frame contains the address in the iterator body where execution should continue when the iterator is resumed.

36 Nested Iterators

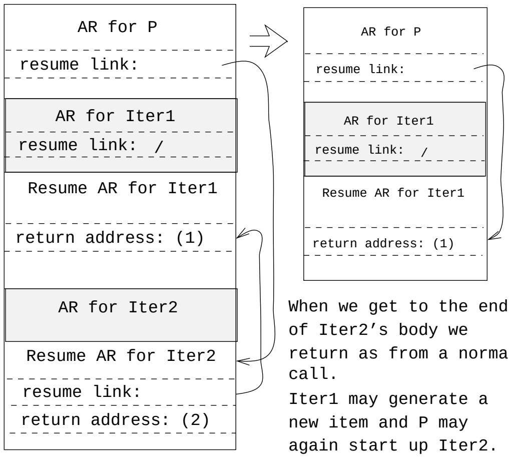
```
for i in Iter1(...)  do
   for j in Iter2(...)  do
      S
```

```
      end
   end
```

37 Nested Iterators...

- Since iterators may be nested, a procedure may have several resume-frames on the stack.
- A new resume frame is inserted **first** in the procedure's **iterator chain**.
- At the end of the **for**-loop body we resume the **first** iterator on the iterator chain:
  1. The first resume frame is unlinked.
  2. We jump to the address contained in the removed frame's return address entry.

38 Nested Iterators...



When we get to the end of Iter2's body we return as from a normal call.

Iter1 may generate a new item and P may again start up Iter2.

39 Simpler Iterator Implementation

```
Iter = iter ( ...  )
   while ...  do
      yield x
   end
end

begin
   for i in Iter(...)  do
      print(i);
   end
end
```

⇓

40 Simpler Iterator Implementation...

```
PROCEDURE Iter (
   Success, Fail :  LABEL;
```

```
   VAR Resume :  LABEL; VAR Result :  T);
BEGIN
   WHILE ...  DO
      ResumeLabel:
      Result := x;
      Resume := ADDR(ResumeLabel);
      GOTO Success
   END;
   GOTO Fail;
END
```

41 Simpler Iterator Implementation. . .

```
VAR Result :  T;
VAR Resume :  LABEL;
BEGIN
   Iter(ADDR(SuccesLabel), ADDR(FailLabel),
         Resume, Result);
   SuccessLabel:
   WRITE Result;
   GOTO Resume;
   FailLabel:
END;
```

Summary

42 Readings and References

1. **Read Scott, pp. 278–284, 135CD-136CD**.
2. Russell R. Atkinson, Barbara H. Liskov, and Robert W. Scheifler: *Aspects of Implementing CLU*, Proceedings ACM National Conference, pp. 123–129, Dec, 1978.
3. Murer, Omohundro, Szyperski: *Sather Iters: Object-Oriented Iteration Abstraction*: `ftp://ftp.icsi.berkeley.edu/pub/techreports/1993/tr-93-045.ps.gz`
4. Todd A. Proebsting: *Simple Translation of Goal-Directed Evaluation*, PLDI'97, pp. 1–6. This paper describes an efficient implementation of Icon iterators.

43 Summary

- Sather (a mini-Eiffel) has adopted an iterator concept similar to CLU's, but tailored to OO languages.
- Iterators function (and can be implemented as) coroutines. Smart compilers should, however, take care to implement "simple" iterators in a more direct way (See the Sather paper).
- Inline expansion of iterators may of course be helpful, but the same caveats as for expansion of procedures apply: code explosion, cache overflow, extra compilation dependencies.