Lecture 4

Building Control Abstractions with Coroutines

iterators, tables, comprehensions, coroutines, lazy iterators, composing iterators

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Hack Your Language!
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Administrativia

Let us know right away if you don't have a team

Optional (but recommended) homework

- It will help you with PA1
- See the web page that shows lecture notes

Today

- iterators (the **for** construct)
- comprehensions
- coroutines
- lazy iterators
- composing lazy iterators
- producer/consumer patterns

For loops and other iterators

Iterators

Whenever a language includes collections

or allows you to build one

we also want constructs for iterating over them

Example: d3 selections (sets of DOM nodes)

The each operator in

`aSelection.each(aFunction)`

is an iterator (implemented as a function)

Let's design a for iterator (behavior)

Desired behavior: say want to iterate from 1 to 10:

```
for x in iter(10) { print x }
```

Q1: Is `iter` a keyword in the language? No, a function.

Q2: What does it return? An iterator function.

```
function iter(n) {
    def i = 0
    function () {
        if (i < n) { i = i + 1; i }
        else { null }  for terminates
}   }
```

Let's design a for iterator (generality)

Q3: In general, what constructs to permit in __ ?

```
for x in __ { print x }
```

A: Any expression that returns an iterator function.

- the syntax of for thus is: **for** *ID* **in** *E* **{** *S* **}**

  def myIter = iter(10)

- these are all legal programs:

```
for x in myIter { S }
for x in myIterArray[2] { S }
for x in myIterFactoryFactory()() { S }   // ☺
```

Let's design a for iterator (scoping)

Q4: What is the scope x?

visible in S

`for x in E { S }`

binding instance for x

Q5: In what environment should *E* be evaluated?

In particular, should the environment include x?

E should be evaluated in e, the environment of **for**.

S should be evaluated in e extended with the binding for x.

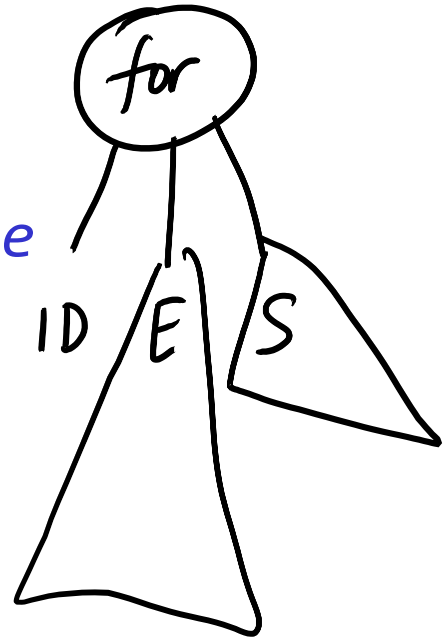
Implementing the **for** iterator

We are done with the design of behavior (semantics).

Now to implementation. We'll desugar it, of course.

```
   for ID in E { S }
-->
{  // a block to introduce new scope
     def $t1 = E     // t1 a temp var
     def ID = $t1()
     while (ID != null) {
           S
           ID = $t1()
     }
}
```

stores iterator function



Side note: the block scope

A new scope can be introduced by desugaring, too:

```
{ S }  --> ( function(){ S } )()
```

This trick is used in JS programs to restrict symbol visibility, ie to implement a simple *module* construct.

Iterator factory for tables

Assume we are using the table (dict) as array:

```
def t = {}; t[0] = 1; t[1] = 2
for x in asArray(t) { print x }
def asArray(tbl) {
      def i = 0
      // your exercise: fill in the rest
      fuction() {
            is t[i] in the array t
            yes : return tbl[i]  i++
            no : return null
      }
}
```

Summary of key concepts

- Iterators and loops are useful for collections and also just to repeat some statement
- We want iterators that work in a modular way, ie, any library can provide a “iterator factory”
- When desugaring for x in E { S }, S turns into a closure that accesses x as a nonlocal variable

Test yourself

Optional homework, posted on the course web page

(understand surprises behind Python comprehensions)

Hint for the optional homework

Why should a desugar rule not touch the body?

for ***id*** in ***E***:

body

should not modify the body.

If you are the compiler, you want to translate **for** without regard for what's in the body. That is, the desugar rule should not have to peek into the subtree body. Otherwise there will be many special cases based on what's in ***body***.

A simple, modular compiler desugars ***body*** recursively

Comprehensions

Comprehensions

A *map* operation over anything that is itererable.

```
[toUpperCase(v) for v in elements([“a”,“b”)]
-->
[“A”, “B”]
```

General syntax:

[***E1*** for ***ID*** in ***E2***]

Can E1, E2 be comprehension expressions?

Comprehensions

Desugaring rule (case specific to this example):

```
[toUpperCase(v) for v in elements(list)]
```

--->

```
$1 = []
for v in elements(list) { append($1, toUpperCase(v)) }
$1
```

Homework: write a general desugar rule

make sure it works work on nested comprehensions

```
mat = [[1, 2, 3],
       [4, 5, 6],
       [7, 8, 9],
      ]
print [[row[i] for row in mat]
                for i in [0, 1, 2]
       ]
--> [[1, 4, 7], [2, 5, 8], [3, 6, 9]]
```

"To avoid apprehension when nesting list comprehensions, read from right to left"

Our abstraction stack is growing nicely

comprehensions

for + iterators

if + while

lambda

Lazy iterators

Print all permutations of a list

```
def permgen(a,n=len(a)) {
   if (n <= 1) {
         print(a)
   } else {
         for i in iter(n) {
               a[n],a[i] = a[i],a[n]
               permgen(a,n-1)
               a[n],a[i] = a[i],a[n]
}  }     }
permgen(["a","b","c"])
```

Now let's try to wrap permgen in an iterator

We want to be able to write

```
for p in permIterator(list) {
    print p
    if (condition(p))
        return p      // find first p with some property
}
```

The loop may iterate only over some permutations, so let's not compute and store all $O(2^n)$ of them in a list. Let's compute them **lazily**, as needed by the loop.

First attempt at wrapping permgen in iterator

```
def permIterator(lst) {
   def permgen(a,n=len(a)) {
         if (n = 1) {
            return a ________     // print(a)
         } else {
            for i in iter(n) {
               a[n],a[i] = a[i],a[n]
               permgen(a,n-1)
               a[n],a[i] = a[i],a[n]
   }     }     }
   lambda () { permgen(lst) }   // the iterator
}
```

What is our stumbling block?

The call stack in `for p in permIterator (lst){S(p)}` when permgen attempts to pass a permutation to for:

```
inside while loop
       at
iteror
permgen(n)
…
permgen(1)
```

Why can't permgen pass the permutation to iterator?

- it would need to return all the way to top of recursion
- this would make to lose all context
- here, context = value of *i* for each recursion level

Ideas for workarounds?

Rewrite permgen *to be iterative.*

Unfortunately, trading recursion for a loop will force us maintain the context (a copy of i for each list element). The code will be uglier.

Reverse the master-slave relationship.

At the moment, **for** is the master. It calls the iterator (slave). Critically, its master decides when to stop iterating, conveniently without having to communicate this decision to the slave. --- Once permgen is the master, we pass to it the body of **for** as a closure. This body is the slave who decides when to stop iterating (it's when condition(p) holds). This decision needs to be communicated to the master permgen. So we need implement a termination protocol between master and slave.

We need something like a goto

Idea: Jump from permgen to the while loop and back,

preserving permgen context on its call stack

Two execution contexts, each with own stack:

while call stack

```
inside while loop
iter-lambda
“call” permgen
```

permgen call stack

```
permgen(n 4)
…          1
permgen(0)
“return” to while
```

Coroutines

Coroutines == “cooperating threads”

Cooperating =

- one thread of control (one PC)
- coroutines themselves decide when control is transferred between them
  - as opposed to an OS scheduler deciding when to preempt the running thread and transfer control (as in timeslicing)
- transfer done with a yield statement

Many flavors of coroutines exist.

Asymmetric Coroutines

Asymmetric: notion of master vs. slave

symmetric c/r can be implemented on top of symmetric

Benefits of asymmetric coroutines:

- easier to understand for the programmer because from the master the transfer looks like an ordinary call
- easier to implement (you'll do it in PA2)

Asymmetric Coroutines

Three constructs:

```
coroutine(body)      master creates cortn
resume(co, arg)      call into cortn co
yield(arg)           return to master
```

Body is a closure

Example

```
def co = create_coroutine(
    lambda(){
        print(1)
        yield
        print(2)
        yield
        print(3)
})      // implicit yield
resume(co) --> 1
resume(co) --> 2
resume(co) --> 3
resume(co) --> error (resuming to a terminated coroutine)
```

Example

```
def co = create_coroutine(lambda(){
      yield 1
      yield 2
      yield 3
})    waiting
print(resume(co)) --> 1
print(resume(co)) --> 2
print(resume(co)) --> 3
resume(co) -->
```

Iterator factory for permgen

```
def permgen(a, n=len(a)) {
      if (n <= 1) { yield(a)  /* print(a) */ }
      else {
            for i=1 to n {
                  a[n],a[i] = a[i],a[n]
                  permgen(a,n-1)
                  a[n],a[i] = a[i],a[n]
}     }     }
def permIterator(lst) {
   def co = coroutine(
                  function(l) { permgen(l); null } )
   function () { resume(co, lst) }
}
```

implicit yield's argument

What can we do with coroutines

define control abstractions impossible with functions:

lazy iterators

push or pull producer-consumer patterns

bactracking

regexes

exceptions

Iterate over multiple collections simultaneously

Problem: Merge two binary search trees

You are given two binary search trees. Print the "merge" of the trees, traversing each tree only once.

We know how to print values of one tree:

```
def preorder(node) {
     if (node) {
          preorder(node.left)
          print(node.key)
          preorder(node.right)
}    }
```

But how do you traverse two trees at once?

Preorder tree iterator

First step: Create a preorder iterator based on c/r.

```
def preorder(node)
     if (node) {
           preorder(node.left)
           yield(node.key)
           preorder(node.right)
     }
     null
}
def preorder_iterator(tree) {
     def co = coroutine(lambda(t){ preorder(t) })
     lambda () { resume(co, tree) }
}
```

Now we do “merge sort” over trees

```
def merge(t1,t2) {
    def it1=preorder_iterator(t1)
    def it2=preorder_iterator(t2)
    def v1=it1()
    def v2=it2()
    while (v1 || v2) {
        if (v1 != null and (v2==null or v1<v2)) {
            print(v1); v1=it1()
        } else {
            print(v2); v2=it2()
        }
    }
}
```

Exercise for you, part 1

Wrap merge(t1,t2) in an iterator so that you can do

```
for v in mergeTreeIterator(tree1,tree2) {
   process(v)
}
function mergeTreeIterator(tree1,tree2) {





}
```

Exercise, part 2

Write an iterator for merging of three trees

```
for v in merge3TreeIterator(tr1,tr2,tr3)
```

Build the iterator on top of mergeTreeIterator

Consumer-Producer Pattern

Create a dataflow on streams

Process the values from merge(t1,t2)

We can apply operations :

```
for v in toUppercaseF(merge(tree1,tree2)) { process(v) }
```

How to create "filters" like `toUpperCaseF`?

A filter element of the pipeline

```
def filter(ant)
    def co = coroutine(function() {
        while (True) {
            --resume antecessor to obtain value
            def x=ant()
            -- yield transformed value
            yield(f(x))
    }    }
    lambda() { resume(co,0) }
}
consumer(filter(filter(producer())))
```

How to implement such pipelines

Producer-consumer patter: often a pipeline structure

- producer → filter → consumer
- All we need to say in code is

```
consumer(filter(producer()))
```

Producer-driven (push) or consumer-driven (pull)

- This decides who initiates resume(). In pull, the consumer resumes to producer who yields datum to consumer.

Each producer, consumer, filter is a coroutine

- Who initiates resume is the main coroutine.
- In for x in producer, the main coroutine is the for loop.

Summary

Coroutines allow powerful control abstractions

- iterators but also backtracking, which we'll cover soon

You will implement coroutines in PA2

- we'll describe the implementation in L5

What you need to know

- Iterators
- Programming with coroutines
- Write push and pull producer-consumer patterns

HW3

- Will prepare you for the project

Glossary

Reading

Required:

- Chapter on coroutines from the Lua textbook

Recommended:

- Python generators are coroutines

Fun:

- More applications of coroutines are in *Revisiting Coroutines*

Acknowledgements

Our course language, including its coroutines, are modeled after Lua, a neat extensible language.

Many examples in this lecture come from *Programming in Lua*, a great book. Read the 1^{st} edition on the web but consider buying the 2^{nd} edition.

http://www.lua.org/pil/

Coroutine examples are from *Revisiting Coroutines*.

Backtracking

Problem: Regex matching

We are given a (an abstract syntax tree) of a regex.
The goal is to decide if the regex matches a string.

Pattern `("abc"|"de")."x"` can be defined as follows:

```
patt = seq(alt(prim("abc"),prim("de")),prim("x"))
```

which effectively encodes the pattern's AST.

seq, alt, prim are coroutines.

Regex matching with coroutines

```
-- matching a string literal (primitive goal)
def prim(str) {
    lambda(S,pos) {
        def len = len(str)
        if (sub(S,pos,pos+len-1)==str) {
            yield(pos+len)
}   }   }
-- alternative patterns (disjunction)
def alt(patt1,patt2) {
    lambda(S,pos) { patt1(S,pos); patt2(S,pos) }
}
-- sequence of sub-patterns (conjunction)
def seq(patt1,patt2) {
    lambda(S,pos) {
        def btpoint=coroutine.wrap(function(){ patt1(S,pos) })
        for npos in btpoint { patt2(S,npos) }
}   }
```

And now the main match routine

```
def match(S,patt) {
    def m=coroutine.wrap(lambda(){ patt(S,0) })
    for (pos in m) {
        if (pos==len(S)) {
            return true
        }
    }
    return false
}
match(“de”, alt(prim("abc"),prim("de")))
   --> true
```