EECS 390 – Lecture 10

Continuations

2/13/24

Agenda

- Restricted Continuations
- First-Class Continuations

Review: First-Class Entities

- We use ***entity*** to denote something that can be named in a program
  - Other terms also used: ***citizen***, ***object***
  - Examples: types, functions, data objects, values
- A ***first-class entity*** is an entity that supports all operations generally available to other entities
  - e.g. can be assigned to a variable, passed to or returned from a function

	C++	Java	Python	Scheme
Functions	sort of	no	yes	yes
Types	no	no	yes	no
Control	no	no	no	yes

Continuations

- A ***continuation*** represents the control state of a program
  - The sequence of active functions
  - Code location within each active function
  - Intermediate results
- A continuation can be ***invoked*** to return control to a previous state
- Only control state is restored, not state of data

Continuation Analogy

Say you're in the kitchen in front of the refrigerator, thinking about a sandwitch [sic]. You take a continuation right there and stick it in your pocket. Then you get some turkey and bread out of the refrigerator and make yourself a sandwitch, which is now sitting on the counter. You invoke the continuation in your pocket, and you find yourself standing in front of the refrigerator again, thinking about a sandwitch. But fortunately, there's a sandwitch on the counter, and all the materials used to make it are gone. So you eat it. :-)

— Luke Palmer

Types of Continuations

- A language may provide restricted forms of continuations that can only be invoked at specific times
  - Subroutines (i.e. functions)
  - Coroutines
  - Exceptions
  - Generators

- Some languages have first-class continuations that can be stored in a variable and invoked at arbitrary times

Subroutines

- A subroutine involves transfer of control between a caller and a callee

- Before control is transferred to the callee, the state of the caller, i.e. its continuation, must be saved
  - Intermediate results stored in caller's activation record
  - Information about how to return control to caller stored in callee's activation record

- Upon completion of call, caller's continuation invoked

```
def foo(x):
    print(x - 1 + bar(x))

def bar(x):
    return x + 1
```

Continuation of foo() invoked

Continuation of foo() must be saved before call to bar()

Abrupt Termination

- In some languages the caller's continuation is only invoked when the callee completes normally

- Other languages allow early termination of a call, also called ***abrupt termination***, with a return statement

```
def foo(x):
    return x
    # dead code
    if x < 0:
        bar(x)
    baz(x)
```

Invoke caller's continuation

Code never reached

Control vs. Data State

- A continuation only represents control state, so invoking it does not restore the state of data

```
def outer():
    x = 0

    def inner():
        nonlocal x
        x += 1

    inner()
    print(x)  # prints 1
```

Invoke continuation of outer()

Value of x is not restored

Coroutines

- Generalize subroutines to allow multiple routines to invoke each other's continuations

```
var q := new queue

coroutine produce
    loop
        while q is not full
            create some new items
            add the items to q
        yield to consume

coroutine consume
    loop
        while q is not empty
            remove some items from q
            use the items
        yield to produce
```

This is pseudocode

Exceptions

- Allow control to be passed to a function further up in the call chain, rather than just the direct caller

```
def foo(x):
    try:
        bar(x)
    except:
        print('Exception')

def bar(x):
    baz(x)

def baz(x):
    raise Exception
```

Save continuation of foo(), add exception handler to handler stack

Invoke continuation of foo(), run exception handler

Generators

- Like a subroutine, but allow execution to be paused and resumed

- Also called ***semicoroutine***
  - Generator can be resumed by any caller
  - However, generator can only yield execution to caller that invoked it

```
def naturals():
    num = 0
    while True:
        yield num
        num += 1
```

Pause execution and yield an item to caller

Generators and Iterators

- In Python, generators implement the same interface as an iterator

- Often simpler to write generator than a class that implements the iterator interface

```
def naturals():
    num = 0
    while True:
        yield num
        num += 1
```

```
>>> numbers = naturals()
>>> next(numbers)
0
>>> next(numbers)
1
>>> next(numbers)
2
```

Finite Generators

- A finite generator automatically raises a `StopIteration` exception when it completes
  - Used by a `for` loop to determine the end of an iterator

```
def range2(start, stop, step=1):
    while start < stop:
        yield start
        start += step
```

```
>>> values = range2(0, 5, 3)
>>> next(values)
0
>>> next(values)
3
>>> next(values)
Traceback (most recent call last):
File "<stdin>", line 1, in <module>
StopIteration
```

```
>>> for i in range2(0, 4):
...     print(i)
...
0
1
2
3
```

Generator Expressions

- Similar to list comprehensions, but produce a generator instead

```
def naturals():
    num = 0
    while True:
        yield num
        num += 1
```

```
>>> negatives = (-i for i in naturals() if i != 0)
>>> next(negatives)
-1
>>> next(negatives)
-2
>>> next(negatives)
-3
```

Generator expression

Map, Reduce, Filter in Python

- Python has built-in map, reduce, and filter
  - Result of `map()` and `filter()` are separate iterator types

```
>>> map(lambda x: x + 1, [1, 4, -3, 7])
<map object at 0x10b438390>
>>> list(map(lambda x: x + 1, [1, 4, -3, 7]))
[2, 5, -2, 8]
```

- Alternate definition of (unary) map with a generator

```
>>> def map_unary(func, iterable):
...     for item in iterable:
...         yield func(item)
...
>>> map_unary(lambda x: x + 1, [1, 4, -3, 7])
<generator object map_unary at 0x1032f3f40>
>>> list(map_unary(lambda x: x + 1, [1, 4, -3, 7]))
[2, 5, -2, 8]
```

First-Class Continuations

- Many functional languages allow the current continuation to be captured in an explicit data structure
- Continuation can be passed as a parameter, returned, saved as a variable, etc.
- Depending on the language, the continuation may be invoked only once or an arbitrary number of times

`call/cc`

- In Scheme, the `call-with-current-continuation` procedure, often abbreviated `call/cc`, creates an object representing the current continuation

- It then calls another procedure with the continuation as the argument

```
(call-with-current-continuation <procedure>)
```

Must be a one-argument procedure

- The called procedure can invoke the continuation, return it, discard it, etc.
  - If the procedure returns normally, the `call/cc` call evaluates to its result (like a standard function call)

```
> (+ 1 (call/cc (lambda (cc) 3)))
4
```

Invoking a Continuation

- A continuation is invoked with a value, which then becomes the "return value" of the `call/cc` call

Call to `call/cc` replaced with value 5

```
> (+ 1
     (call/cc (lambda (cc)
                (cc 5)
                3
              )
     )
  )
6
```

Continuation invoked with value 5

Not evaluated

This is a generalization of return – compare to `return 5` in Python, which invokes the continuation of the caller with `5`.

Storing a Continuation

- Allows a continuation to be invoked multiple times

```
> (define var (call/cc (lambda (cc) cc)))
var
> (define cont var)
cont
> (cont 3)
var
> var
3
> (cont 4)
var
> var
4
```

Becomes (define var 3)

Becomes (define var 4)

Example: Error Handling

- Using a stored continuation for error recovery:

```
(define error-cont '())

(define (error-setup cont)
  (set! error-cont cont)
  #f
)

(define (error message)
  (display "Error: ")
  (display message)
  (newline)
  (error-cont #t)
)
```

Store continuation to allow it to be invoked later

Invoke stored continuation

Example: Error Handling

- Interactive loop with error handling

```
(define (read-all)
  (call-with-current-continuation error-setup)
  (display "read> ")
  (flush-output)
  (let ((datum (read-datum)))
    (if (not (eof-object? datum))
        (begin (write datum)
               (newline)
               (read-all)
        )
        (newline)
    )
  )
)
```

Store continuation for this point in the loop

error invokes the continuation for this point

error may be invoked here

```
> (read-all)
read> "hello world"
"hello world"
read> #(dot in a . vector)
Error: unexpected dot token
read> (dot in a . list)
(dot in a . list)
```

Continuations and Goto

- First-class continuations are often criticized for the same reasons as goto, since they allow unstructured transfer of control

- As with goto, continuations should be used judiciously
  - Implementing more restricted forms of control transfer such as exceptions
  - Adhering to conventions as in continuation-passing style

Aside: Yin-Yang Puzzle

- Prints out unary representations of the natural numbers

```scheme
(let* ((yin ((lambda (cc) (display "@") cc)
             (call/cc (lambda (c) c))
            ))
       (yang ((lambda (cc) (display "*") cc)
              (call/cc (lambda (c) c))
             )))
  (yin yang)
)
```

```
@*@**@***@****@*****@******@*******@********@*********@**********@
***********@************@*************@**************@************
***@****************@*****************@******************@********
***********@********************@*********************@***********
***********@***********************@************************@*****
********************@**************************@******************
*********@****************************@***************************
**@******************************@*******************************@
```