CS450

Structure of Higher Level Languages

Lecture 32: Monadic continuations

Tiago Cogumbreiro

Today we will learn about...

- Continuations
- Continuation-Passing Style (CPS)
- Encoding exceptions with CPS
- Handling exceptions in Racket
- Yield

Other references: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Continuations

What is a continuation?

A technique to abstract control flow. It reifies an execution point as a pair that consists of:

- the program state (eg, the environment)
- the remaining code to run (eg, the term)

Used to encode

- **exceptions**
- **generators**
- coroutines (lightweight threads)

How can we represent continuations?

- continuation-passing style (inversion of control)
- first-class construct (Racket)

Continuation-passing style (CPS)

Q: How do we abstract computation?

Continuation-passing style (CPS)

Q: How do we abstract computation?

A: Inversion of control

> Hollywood principle: Don't call us, we'll call you.

- the objective is to have control over where a function returns to (its continuation)
- make ***returning a value*** a function call

Direct style

```
(define (f x)
  (+ x 2))
```

CPS

```
(define (f x ret)
  (ret (+ x 2)))
```

Where have we seen CPS?

- Remember when we implemented the tail-recursive optimization?

Before

```
(define (map f l)
  (cond [(empty? l) l]
        [else (cons (f (first l)) (map f (rest l)))]))
```

After

```
(define (map f l)
  (define (map-iter l accum)
    (cond [(empty? l) (accum l)]
          [else (map-iter (rest l) (lambda (x) (accum (cons (f (first l)) x))))]))
  (map-iter l (lambda (x) x)))
```

Function `map-iter` is the CPS-version of `map`!

Encoding exceptions with CPS

```
(define (safe-/ x y)
  (lambda (ok err)
    (cond [(= 0 y) (err 'division-by-zero)]
          [else (ok (/ x y))])))
```

Example 1

```
; Print to standard-output if OK and throw an exception if not
((safe-/ 2 1) display error)
; error: division-by-zero
((safe-/ 2 0) display error)
```

Example 2

> How can we chain two divisions together?

```
(/ (/ 10 2) 3)
```

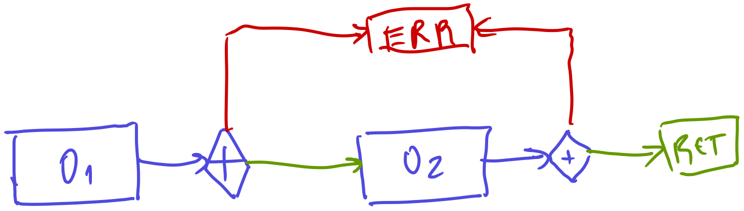
Monadic Continuation-Passing Style

Exceptions Monadic+CPS

```
; Returns x via the return function
(define (return x)
  (lambda (ret err)
    (ret x)))
; Returns x via the error function
(define (raise x)
  (lambda (ret err)
    (err x)))
; Monadic-bind on CPS-style code
(define (cps-bind o1 o2)
  (lambda (ret err)
    (o1 (lambda (res) ((o2 res) ret err)) err)))
; The try-catch operation
(define (try o1 o2)
  (lambda (ret err)
    (o1 ret (lambda (res) ((o2 res) ret err)))))
```

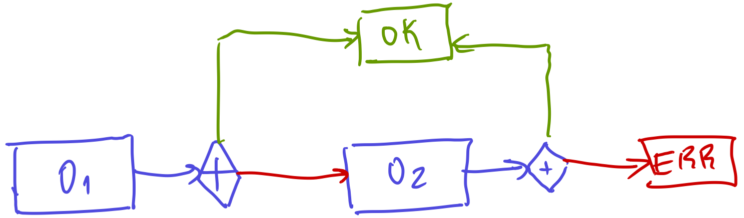
Bind

bind runs o1 and the ok-continuation of o1 is running o2



Try

try runs o1 and the error-continuation is running o2



Revisiting safe-division with monadic API

> Thanks to functional programming and monads, we can easily design `try-catch` on top of a regular computation.

```
(define (&/ x y)
  (cond [(= 0 y) (raise 'division-by-zero)]
        [else (return (/ x y))]))
```

Examples

```
; 1. Run a division by zero and get an exception
(run? (&/ 1 0) (cons 'error 'division-by-zero))
; 2. Run a division by zero and use try-catch to return OK
(run?
  (try
    (&/ 1 0)
    (lambda (err) (return 10)))
  (cons 'ok 10))
; 3. Use bind in a more intricate computation
(run?
  (do
    x <- (&/ 3 4)
    (try
      (&/ x 0)
      (lambda (err) (return 10))))
  (cons 'ok 10))
```

Exceptions in Racket

How do we catch exception in Racket?

> We must use the `with-handler` construct that takes the exception type, and the code that is run when the exception is raised.

```
#lang racket
(define (on-err e)
  ; Instead of returning what we were doing, just return #f
  #f)
(with-handlers ([exn:fail:contract:divide-by-zero? on-err])
  (/ 1 0))
```

First-class continuations in Racket

First-class support continuations in Racket

Inversion of control

> `(call/cc f)` captures the surrounding code as a **continuation**, and passes that continuation to function `f`.

```
(+ 1 2 (call/cc f) 4 5)
```

becomes

```
(f (lambda (x) (+ 1 2 x 4 5)))
```

Recommended reading

- Many examples using call/cc

Yield

Another way to write streams

(Or, returning streams of values)

Yield: abstracting lazy evaluation

> `yield` allows generalizing returning a finite stream of values (rather than just one). `yield` actually returns a value, so the caller can interact with the caller. In the following example, `yield` allows processing multiple files ensuring the garbage collector does not load everything to memory eagerly.

```python
# source: https://github.com/cogumbreiro/apisan/blob/master/analyzer/apisan/parse/explorer.p
def parse_file(filename):
  # ...
  for root in xml:
      tree = ExecTree(ExecNode(root, resolver=resolver)) # load a possibly big file
      yield tree
      del tree # garbage collect the memory
## User code
for xml in parse_file(somefile):
  handle(xml) # handle the xml object
```

Implementing `yield`

Let us implement `yield` in Racket!

- Yield: Mainstream Delimited Continuations. TPDC. 2011

Papers are still being published in top Programming Language conferences on this subject:

- Theory and Practice of Coroutines with Snapshots. ECOOP. 2018

Yield summary

1. Run a CPS computation normally until `(yield x)`
2. The execution of `(yield x)` should suspend the current execution
3. There must exist an execution context that can run suspendable computations

Implementation

- Yield is a regular CPS-monadic operation but it returns a suspended object, rather than using `ok` or `err`.

```
(struct susp (value ok) #:transparent)

(define (yield v)
  (lambda (ok err) (susp v ok)))

(define (resume s)
  ((susp-ok s) (void)))
```

- (Demo...)