Programming Abstractions

Week 14-1: Continuation Passing Style

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Continuations: Our final topic!

Suppose expression E contains a subexpression S

The **continuation** of S in E consists of all of the steps needed to complete E after the completion of S

Example: `(- 4 (+ 1 1))`

- The subexpression S, (+ 1 1) is called the redex ("reducible expression")
- The continuation is `(- 4 □)` where □ takes the place of S

Example: `(displayln (foo (bar (* 2 3))))`

- The continuation of `(bar (* 2 3))` is `(displayln (foo □))`

What is the continuation of `(fact (sub1 n))` in the expression
`(* n (fact (sub1 n)))`

A. `(* n (fact (sub1 n)))`

B. `(* n (fact (sub1 □)))`

C. `(* n (fact □))`

D. `(* n □)`

E. □

A continuation is really a dynamic construct

A continuation is determined by the expression's evaluation context at run time

```
(define (fact n)
  (cond [(zero? n) 1]
        [else (* n (fact (sub1 n)))]))
```

At the point 1 is evaluated in the call `(fact 0)`, the continuation is □

At the point 1 is evaluated in the call `(fact 1)`, the continuation is `(* 1 □)`

At the point 1 is evaluated in the call `(fact 2)`, the continuation is `(* 2 (* 1 □))`

Key: The continuation is **all** the rest of computation

Continuations can be quite complicated!

Starting with a positive integer n, construct a sequence where each successive term is obtained by the current term n

- If the current term n is 1, then stop.
- If the current term n is even, the next term is n/2
- If the current term n is odd, the next term is 3n+1

(The Collatz conjecture says that the sequence produced starting with any positive integer eventually stops.)

Continuations of the Collatz computation

Continuations of the Collatz computation

```
(define (collatz n)
  (cond [(= 1 n) '(1)]
        [(even? n) (cons n (collatz (/ n 2)))]
        [else (cons n (collatz (add1 (* 3 n))))]))
```

Continuations of `'(1)` in the call `(collatz n)` for several values of `n`

Continuations of the Collatz computation

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(define (collatz n)
  (cond [(= 1 n) '(1)]
        [(even? n) (cons n (collatz (/ n 2)))]
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```

Continuations of `'(1)` in the call `(collatz n)` for several values of `n`

- `n = 1: □`

Continuations of the Collatz computation

```
(define (collatz n)
  (cond [(= 1 n) '(1)]
        [(even? n) (cons n (collatz (/ n 2)))]
        [else (cons n (collatz (add1 (* 3 n))))]))
```

Continuations of `'(1)` in the call `(collatz n)` for several values of `n`

- `n = 1: □`
- `n = 2: (cons 2 □)`

Continuations of the Collatz computation

```
(define (collatz n)
  (cond [(= 1 n) '(1)]
        [(even? n) (cons n (collatz (/ n 2)))]
        [else (cons n (collatz (add1 (* 3 n))))]))
```

Continuations of `'(1)` in the call `(collatz n)` for several values of `n`

- `n = 1: □`
- `n = 2: (cons 2 □)`
- `n = 3:`
  `(cons 3 (cons 10 (cons 5 (cons 16 (cons 8 (cons 4 (cons 2 □)))))))`

Continuations of the Collatz computation

```
(define (collatz n)
  (cond [(= 1 n) '(1)]
        [(even? n) (cons n (collatz (/ n 2)))]
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```

Continuations of `'(1)` in the call `(collatz n)` for several values of `n`

- `n = 1: □`
- `n = 2: (cons 2 □)`
- `n = 3:`
  `(cons 3 (cons 10 (cons 5 (cons 16 (cons 8 (cons 4 (cons 2 □)))))))`
- `n = 4: (cons 4 (cons 2 □))`

Continuations of the Collatz computation

```
(define (collatz n)
  (cond [(= 1 n) '(1)]
        [(even? n) (cons n (collatz (/ n 2)))]
        [else (cons n (collatz (add1 (* 3 n))))]))
```

Continuations of `'(1)` in the call `(collatz n)` for several values of `n`

- `n = 1: □`
- `n = 2: (cons 2 □)`
- `n = 3:`
  `(cons 3 (cons 10 (cons 5 (cons 16 (cons 8 (cons 4 (cons 2 □)))))))`
- `n = 4: (cons 4 (cons 2 □))`
- `n = 5: (cons 5 (cons 16 (cons 8 (cons 4 (cons 2 □)))))`

```
(define (length lst)
  (cond [(empty? lst) 0]
        [else (add1 (length (rest lst)))]))
```

What is the continuation at the point `0` is evaluated in the call `(length '(a b c))`

A. `3`

B. `(length lst)`

C. `(add1 (length □))`

D. `(add1 (add1 (add1 0)))`

E. `(add1 (add1 (add1 □)))`

Viewing continuations as procedures

We can view a continuation as a procedure of one argument

Example: `(- 4 (+ 1 1))`

- The continuation is `(- 4 □)` where □ takes the place of S
- `(λ (x) (- 4 x))`

Example: `(displayln (foo (bar (* 2 3))))`

- The continuation of `(bar (* 2 3))` is `(displayln (foo □))`
- `(λ (x) (displayln (foo x)))`

Continuation-passing style

A new way to implement recursive procedures

- Each procedure has an extra **continuation** parameter typically called `k`
- The continuation `k` says what to do with the result

Continuation-passing style example

Summing numbers in a list

```
(define (sum-k lst k)
  (cond [(empty? lst) (k 0)]
        [else (sum-k (rest lst)
                     (λ (x) (k (+ x (first lst)))))]))
```

Two things to notice:

- In the base case, we call the continuation with our base value `(k 0)`
- In the recursive case, we pass a new continuation procedure that calls `k` with the result of adding `x` to the head of `lst`

Calling our function

What should we use as the top-level continuation when we call sum-k?

```
(define (sum-k lst k)
  (cond [(empty? lst) (k 0)]
        [else (sum-k (rest lst)
                     (λ (x) (k (+ x (first lst)))))]))
```

It depends what we want to do with it, typically, we'd want to return the value

- We can use `(λ (x) x)` which Racket predefines as `identity`

```
(sum-k '(1 2 3 4) identity) => 10
```

Compare with accumulator-passing style

```
(define (sum-k lst k)
  (cond [(empty? lst) (k 0)]
        [else (sum-k (rest lst)
                     (λ (x) (k (+ x (first lst)))))]))

(define (sum-a lst acc)
  (cond [(empty? lst) acc]
        [else (sum-a (rest lst) (+ acc (first lst)))]))
```

In CPS, the extra parameter is a procedure that says what to do with the result of the computation

In APS, the extra parameter is the intermediate value in the computation

CPS guidelines

Continuations are procedures with 1 argument which is the result of recursive call

The recursive procedure has a continuation parameter, `k`

The continuation argument is applied to every branch of computation (think base case and recursive case)

At the top-level, the continuation is usually identity

Recursive calls must be tail-recursive

Reverse in CPS

```
(define (reverse-k lst k)
  (cond [(empty? lst) (k empty)]
        [else (reverse-k (rest lst)
                         (λ (x) (k (append x (list (first lst))))))]))
```

Note: this is spectacularly inefficient

- `(reverse lst)` takes time O(n) where n is the length of the list
- `(reverse-k lst identity)` takes time $O(n^2)$

Append in CPS

```
(define (append-k lst1 lst2 k)
  (cond [(empty? lst1) (k lst2)]
        [else (append-k (rest lst1)
                        lst2
                        (λ (x) (k (cons (first lst1) x))))]))
```

Comparing append in CPS to normal recursion

```
(define (append-k lst1 lst2 k)
  (cond [(empty? lst1) (k lst2)]
        [else (append-k (rest lst1)
                        lst2
                        (λ (x) (k (cons (first lst1) x))))]))
(define (append lst1 lst2)
  (cond [(empty? lst1) lst2]
        [else (cons (first lst1)
                    (append (rest lst1) lst2))]))
```

In `append`, the continuation of the recursive call is `(cons (first lst1) □)` *plus* all of the other earlier recursive calls (example on next slide)

This is identical to the passed-in continuation in `append-k` where `k` is the other recursive calls

Continuation example

Appending '(1 2 3) to '(a b c)

Step	`lst1`	append's recursive continuation	k argument to append-k's recursive call (expanded)
0	`'(1 2 3)`	`(cons 1 □)`	`(λ (x) (k (cons 1 x)))`
1	`'(2 3)`	`(cons 1 (cons 2 □))`	`(λ (x) (k (cons 1 (cons 2 x))))`
2	`'(3)`	`(cons 1 (cons 2 (cons 3 □)`	`(λ (x) (k (cons 1 (cons 2 (cons 3 x)))))`
3	`'()`	—	—

- append's continuations also include the top-level continuation the table omits
- `k` in append-k's recursive calls aren't expanded, they're the closure `(λ (x) (k (cons (first lst1) x)))` with `k` bound to the previous closure and `lst1` bound to the corresponding `lst1` argument in the table
- CPS makes the continuations explicit

So what good is this?

Programming with explicit continuations gives you a lot of control

- E.g., you can *ignore* the continuation that is built up and do something else!

Consider our standard sum procedure

```
(define (sum lst)
  (cond [(empty? lst) 0]
        [else (+ (first lst) (sum (rest lst)))]))
```

Suppose we want to modify this to return `#f` if `lst` contains an element that isn't a number

Failed attempt

```
(define (sum lst)
  (cond [(empty? lst) 0]
        [(not (number? (first lst))) #f]
        [else (+ (first lst) (sum (rest lst)))]))
```

If we call this with `'(1 2 3 steve 4)`, then at some point, the else condition will attempt to add `3` and `'steve` and crash!

A working attempt with CPS

Since CPS uses tail-recursion, we can ignore our built-up continuation and return #f

```
(define (sum-k lst k)
  (cond [(empty? lst) (k 0)]
        [(not (number? (first lst))) #f]
        [else (sum-k (rest lst)
                     (λ (x) (k (+ x (first lst)))))]))

(sum-k '(1 2 3 steve 4) identity) => #f
```

A better approach

We can use an error continuation

- This lets the caller decide what to do with the error

```
(define (sum-k lst k err)
  (cond [(empty? lst) (k 0)]
        [(not (number? (first lst))) (err (first lst))]
        [else (sum-k (rest lst)
                     (λ (x) (k (+ x (first lst))))
                     err)]))

> (sum-k '(1 2 3 steve 4)
         identity
         (λ (bad) (printf "Bad element: ~s\n" bad)))
Bad element: steve
```

Some more CPS examples

`map-k`: CPS version of `map`

`collatz-k`: CPS version of `collatz`

`fib-k`: CPS version of `fib`

`map-k-k`: CPS version of `map` that takes a CPS `f`