Continuations

6.037 - Structure and Interpretation of Computer Programs

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Lecture 7A

Deferred operations

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(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)
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..“The program ran out of memory”

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- What if we never had any deferred operations?
- Instead of *returning a value* with deferred operations, the function is passed a *continuation procedure*, which we call to return a value
- Which means that all function calls are *tail-recursive*

Simple CPS example

```
(define (add-17 x)
  (+ x 17))
```

Simple CPS example

```
(define (add-17 x)
  (+ x 17))

(define (add-17 x cont)
  (cont (+ x 17)))
```

Factorial in CPS

```
(define (factorial n)
  (if (= n 0)
      1
      (* n (factorial (- n 1)))))
```

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(define (factorial n cont)
  (if (= n 0)
      (cont 1)
      (factorial (- n 1)
                 (lambda (x) (cont (* n x))))))
```

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(factorial 10 (lambda (x) x))
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```

- No deferred operations
- We craft a **new** continuation, based on the previous one, and pass that to our recursive call
- Asks the question, “What will I do with the return value of the recursive call?”
- “Multiply it by `n`, and call *my* continuation with that value”

Sum-interval

```
(define (sum-interval a b)
  (if (= a b)
      a
      (+ a (sum-interval (+ a 1) b))))

(define (cs-sum-interval a b cont)
  (if (= a b)
      (cont a)
      (cs-sum-interval
       (+ a 1)
        b
       (lambda (x) (cont (+ a x))))))
```

Append

```
(define (append L1 L2)
  (if (null? L1)
      L2
      (cons (car L1) (append (cdr L1) L2))))
```

Append

```
(define (append L1 L2)
  (if (null? L1)
      L2
      (cons (car L1) (append (cdr L1) L2))))

(define (cs-append L1 L2 cont)
  (if (null? L1)
      (cont L2)
      (cs-append
       (cdr L1)
       L2
       (lambda (appended-cdr)
        (cons (car L1) appended-cdr)))))
```

Append, done right

```
(define (append L1 L2)
  (if (null? L1)
      L2
      (cons (car L1) (append (cdr L1) L2))))

(define (cs-append L1 L2 cont)
  (if (null? L1)
      (cont L2)
      (cs-append
       (cdr L1)
       L2
       (lambda (appended-cdr)
        (cont (cons (car L1) appended-cdr))))))
```

Flatten

```
(define (flatten tree)
  (cond ((null? tree) '())
        ((not (pair? tree)) (list tree))
        (else (append (flatten (car tree))
                      (flatten (cdr tree))))))
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(define (cs-flatten tree cont)
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        (else (cs-flatten
          (car tree)
          (lambda (car-leaves)
            (cs-flatten
             (cdr tree)
             (lambda (cdr-leaves)
               (cont
                (append car-leaves cdr-leaves)
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```
(define (divide a b success fail)
    (if (= b 0)
      (fail "divide-by-zero")
      (success (/ a b))))
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Control flow

- Continuation-passing style is also very useful in controlling program flow
- Error handling and exceptions is a classic case:

```
(define (divide a b success fail)
    (if (= b 0)
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```

- Also asynchronous procedure calls

Continuations in the interpreter

We can write a Scheme interpreter in continuation-passing style

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We can write a Scheme interpreter in continuation-passing style

```
(define (driver-loop)
  (prompt-for-input input-prompt)
  (let ((input (read)))
    (if (eq? input '**quit**)
        'c-eval-done
        (c-eval
         input
         the-global-environment
         (lambda (output)
           (announce-output output-prompt)
           (display output)
           (driver-loop))))))
```

```
(define (c-eval exp env cont)
  (cond ((self-evaluating? exp)
         (cont exp))
        ((variable? exp)
         (cont (lookup-variable-value exp env)))
        ((quoted? exp)
         (cont (text-of-quotation exp)))
        ((assignment? exp)
         (eval-assignment exp env cont))
        ((definition? exp)
         (eval-definition exp env cont))
        ((if? exp) (eval-if exp env cont))
        ((lambda? exp)
         (cont (make-procedure (lambda-parameters exp)
                               (lambda-body exp) env)))
        ((begin? exp)
         (eval-sequence (begin-actions exp) env cont))
        ((cond? exp)
         (c-eval (cond->if exp) env cont))
        ...
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        ((cond? exp)
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        ...
```

```
(define (eval-if exp env cont)
  (c-eval
   (if-predicate exp) env
   (lambda (test-value)
     (if test-value
         (c-eval (if-consequent exp) env cont)
         (c-eval (if-alternative exp) env cont)))))
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(define (eval-sequence exps env cont)
  (if (last-exp? exps)
      (c-eval (first-exp exps) env cont)
      (c-eval (first-exp exps) env
       (lambda (ignored)
         (eval-sequence
          (rest-exps exps)
          env cont)))))
```

Continuations with the interpreter

- What if the evaluator made its continuations available to the language?

Continuations with the interpreter

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- `call-with-current-continuation` (a.k.a. `call/cc`)

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```
;; Special form for evaluator
(define (eval-call-with-current-continuation exp env cont)
  (c-eval
   (call/cc-proc exp) env
   (lambda (proc-to-call)
     (c-apply proc-to-call
              (list (make-continuation cont))
              cont))))

;; in c-apply
        ((continuation? procedure)
         (apply (continuation-internal-cont procedure)
                arguments))
```

call/cc example

```
(+ (* 3 (call-with-current-continuation
          (lambda (cont)
            (cont 5))))
   10)
```

call/cc example

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(+ (* 3 (call-with-current-continuation
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; => 25
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(define c #f)
(+ (* 3 (call-with-current-continuation
          (lambda (cont)
            (set! c cont)
            (cont 5))))
   10)
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            (cont 5))))
   10)
; => 25
(c 6)
; => 28
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(c 6)
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call/cc explained

- `call-with-current-continuation` (or `call/cc`, as it is usefully shortened to) takes a procedure as an argument, and passes it the evaluator's current continuation

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- . . . or the procedure could just call the continuation it was given. *Which is exactly identical in meaning!*

call/cc explained

- `call-with-current-continuation` (or `call/cc`, as it is usefully shortened to) takes a procedure as an argument, and passes it the evaluator's current continuation
- The return value of `call/cc` is the same as the return value of the procedure
- . . . or the procedure could just call the continuation it was given. *Which is exactly identical in meaning!*
- The continuation of the `call/cc` expression, the continuation of the procedure that it calls, and the **value** that it passes as an argument to that procedure, are all the same!

Storing continuations

- Stored continuations can be saved away to “jump back” at any later point in time

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(define cont 'uninitialized)
(if (call/cc (lambda (c)
               (set! cont c)
               #t))
    'something
    'other-thing)
```

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; => 'something
(cont #f)
```

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(define cont 'uninitialized)
(if (call/cc (lambda (c)
               (set! cont c)
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    'something
    'other-thing)
; => 'something
(cont #f)
; => 'other-thing
```

```
(define (fib-func)
  (let ((prev 0)
        (cur 1))
    (define (loop)
      (define next (+ prev cur))
      (set! prev cur)
      (set! cur next)
      prev)
    loop))
```

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(define (fib-func)
  (let ((prev 0)
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    loop))
(define test (fib-func))
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  (let ((prev 0)
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      prev)
    loop))
(define test (fib-func))
(test) ; => 1
```

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(define (fib-func)
  (let ((prev 0)
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      (define next (+ prev cur))
      (set! prev cur)
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      prev)
    loop))
(define test (fib-func))
(test) ; => 1
(test) ; => 1
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(define (fib-func)
  (let ((prev 0)
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    loop))
(define test (fib-func))
(test) ; => 1
(test) ; => 1
(test) ; => 2
```

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(define (fib-func)
  (let ((prev 0)
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    (define (loop)
      (define next (+ prev cur))
      (set! prev cur)
      (set! cur next)
      prev)
    loop))
(define test (fib-func))
(test) ; => 1
(test) ; => 1
(test) ; => 2
(test) ; => 3
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(define (fib-func)
  (let ((prev 0)
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    (define (loop)
      (define next (+ prev cur))
      (set! prev cur)
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      prev)
    loop))
(define test (fib-func))
(test) ; => 1
(test) ; => 1
(test) ; => 2
(test) ; => 3
(test) ; => 5
```

```
(define resume 'uninitialized)
(define (fib-cont)
  (let ((prev 0)
        (cur 1))
    (define (loop)
      (define next (+ prev cur))
      (set! prev cur)
      (set! cur next)
      (if (call/cc
           (lambda (c)
             (set! resume (lambda () (c #f)))
             (c #t)))
          prev
          (loop)))
    (loop)))
```

```
(define resume 'uninitialized)
(define (fib-cont)
  (let ((prev 0)
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    (define (loop)
      (define next (+ prev cur))
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          (loop)))
    (loop)))
(fib-cont) ; => 1
```

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(define resume 'uninitialized)
(define (fib-cont)
  (let ((prev 0)
        (cur 1))
    (define (loop)
      (define next (+ prev cur))
      (set! prev cur)
      (set! cur next)
      (if (call/cc
           (lambda (c)
             (set! resume (lambda () (c #f)))
             (c #t)))
          prev
          (loop)))
    (loop)))
(fib-cont) ; => 1
(resume)   ; => 1
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(fib-cont) ; => 1
(resume)   ; => 1
(resume)   ; => 2
```

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  (let ((prev 0)
        (cur 1))
    (define (loop)
      (define next (+ prev cur))
      (set! prev cur)
      (set! cur next)
      (if (call/cc
           (lambda (c)
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          prev
          (loop)))
    (loop)))
(fib-cont) ; => 1
(resume)   ; => 1
(resume)   ; => 2
(resume)   ; => 3
```

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      (if (call/cc
           (lambda (c)
             (set! resume (lambda () (c #f)))
             (c #t)))
          prev
          (loop)))
    (loop)))
(fib-cont) ; => 1
(resume)   ; => 1
(resume)   ; => 2
(resume)   ; => 3
(resume)   ; => 5
```

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- Used by Mac OS 9, Windows 3.1