(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (+ (run-in-circles (cdr l)))))

“The program ran out of memory”
Deferred operations

(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (+ (run-in-circles (cdr l))))

(run-in-circles the-cons)
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (+ (run-in-circles (cdr l)))))

(run-in-circles the-cons)
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (+ (run-in-circles (cdr l)))))

(run-in-circles the-cons)

..
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (+ (run-in-circles (cdr l)))))

(run-in-circles the-cons)

."The program ran out of memory"
Tail recursion in action

(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))

(run-in-circles the-cons)
Tail recursion in action

(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))

(run-in-circles the-cons)

.
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))

(run-in-circles the-cons)

..
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))

(run-in-circles the-cons)

...
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))

(run-in-circles the-cons)

.....
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))

(run-in-circles the-cons)

........
Tail recursion in action

(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))

(run-in-circles the-cons)

.............
(define the-cons (cons 1 #f))
(set-cdr! the-cons the-cons)

(define (run-in-circles l)
  (run-in-circles (cdr l)))

(run-in-circles the-cons)
What if we never had any deferred operations?
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.
What if we never had any deferred operations?
Instead of \textit{returning a value} with deferred operations, the function is passed a \textit{continuation procedure}, which we call to return a value.
Which means that all function calls are \textit{tail-recursive}. 

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

(define (add-17 x cont)
  (cont (+ x 17)))
(define (factorial n)
  (if (= n 0)
      1
      (* n (factorial (- n 1)))))

(factorial 10 (lambda (x) x))

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

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

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

(factorial 10 (lambda (x) x))
(define (factorial n cont)
  (if (= n 0)
      (cont 1)
      (factorial (- n 1)
        (lambda (x) (cont (* n x))))))

(factorial 10 (lambda (x) x))

- No deferred operations
(define (factorial n cont)
  (if (= n 0)
    (cont 1)
    (factorial (- n 1)
      (lambda (x) (cont (* n x))))))

(factorial 10 (lambda (x) x))

- No deferred operations
- We craft a new continuation, based on the previous one, and pass that to our recursive call
(define (factorial n cont)
  (if (= n 0)
    (cont 1)
    (factorial (- n 1)
      (lambda (x) (cont (* n x))))))

(factorial 10 (lambda (x) x))

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

(factorial 10 (lambda (x) x))

- 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”
(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))))))
(define (append L1 L2)
  (if (null? L1)
      L2
      (cons (car L1) (append (cdr L1) L2)))))
(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)))))
(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))))))
(define (flatten tree)
  (cond ((null? tree) '())
        ((not (pair? tree)) (list tree))
        (else (append (flatten (car tree))
                      (flatten (cdr tree))))))

(define (cs-flatten tree cont)
  (cond ((null? tree) (cont '()))
        ((not (pair? tree)) (cont (list tree))
        (else (cs-flatten (car tree)
                         (lambda (car-leaves)
                              (cs-flatten (cdr tree)
                                          (lambda (cdr-leaves)
                                               (cont (append car-leaves cdr-leaves))))))))))
(define (flatten tree)
  (cond ((null? tree) '())
    ((not (pair? tree)) (list tree))
    (else (append (flatten (car tree))
                  (flatten (cdr tree))))))

(define (cs-flatten tree cont)
  (cond ((null? tree) (cont '()))
    ((not (pair? tree)) (cont (list tree)))))
  (else (cs-flatten
         (car tree)
         (lambda (car-leaves)
            (cs-flatten
             (cdr tree)
             (lambda (cdr-leaves)
                (cont
                 (append car-leaves cdr-leaves)
                 ))))))))}
(define (flatten tree)
  (cond ((null? tree) '())
        ((not (pair? tree)) (list tree))
        (else (append (flatten (car tree))
                      (flatten (cdr tree))))))

(define (cs-flatten tree cont)
  (cond ((null? tree) (cont '()))
        ((not (pair? tree)) (cont (list tree)))
        (else (cs-flatten
carin tree
  (lambda (car-leaves)
    (cs-flatten
cardin tree
cdr tree
  (lambda (cdr-leaves)
    (cont
      (append car-leaves cdr-leaves)
    ))))))))
(define (flatten tree)
  (cond ((null? tree) '())
        ((not (pair? tree)) (list tree))
        (else (append (flatten (car tree))
                       (flatten (cdr tree))))))

(define (cs-flatten tree cont)
  (cond ((null? tree) (cont '()))
        ((not (pair? tree)) (cont (list tree)))
        (else (cs-flatten
               (car tree)
               (lambda (car-leaves)
                (cs-flatten
                 (cdr tree)
                 (lambda (cdr-leaves)
                  (cont
                   (append car-leaves cdr-leaves)
                   ))))))))
(define (flatten tree)
  (cond ((null? tree) '())
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                      (flatten (cdr tree))))))

(define (cs-flatten tree cont)
  (cond ((null? tree) (cont '()))
        ((not (pair? tree)) (cont (list tree)))
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                (car tree)
                (lambda (car-leaves)
                  (cs-flatten
                   (cdr tree)
                   (lambda (cdr-leaves)
                     (cont
                      (append car-leaves cdr-leaves)
                      ))))))))
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  (cond ((null? tree) '())
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  (cond ((null? tree) (cont '()))
        ((not (pair? tree)) (cont (list tree)))
        (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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  (cond ((null? tree) '())
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                      (flatten (cdr tree))))))

(define (cs-flatten tree cont)
  (cond ((null? tree) (cont '()))
        ((not (pair? tree)) (cont (list tree)))
        (else (cs-flatten
               (car tree)
               (lambda (car-leaves)
               (cs-flatten
                 (cdr tree)
                 (lambda (cdr-leaves)
                 (cont
                  (append car-leaves cdr-leaves)
                  ))))))))
Continuation-passing style is also very useful in controlling program flow.
Control flow

- Continuation-passing style is also very useful in controlling program flow
- Error handling and exceptions is a classic case:
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)
      (fail "divide-by-zero")
      (success (/ a b)))))
```
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)
      (fail "divide-by-zero")
      (success (/ a b))))
```

- Also asynchronous procedure calls
We can write a Scheme interpreter in continuation-passing style.
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 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))
...
(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))
...
(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))
        ...)
(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-quotuation 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))
...
(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)))))}
(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))))
  )))

(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
            (eval-sequence
              (rest-exps exps) env cont)
            env cont))))))
Continuations with the interpreter

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

```scheme
(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))
```
What if the evaluator made its continuations available to the language?

call-with-current-continuation (a.k.a. call/cc)
What if the evaluator made its continuations available to the language?

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

;; 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

(+ (* 3 (call-with-current-continuation
    (lambda (cont)
      (cont 5)))
   10)
 ; => 25

(define c #f)
(+ (* 3 (call-with-current-continuation
    (lambda (cont)
      (set! c cont)
      (cont 5)))
   10)
 ; => 25
(c 6)
 ; => 28
(+ 100 (c 6))
 ; => 28

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call/cc example

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

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

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

(+ (* 3 (call-with-current-continuation
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call/cc example

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(define c #f)
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    (lambda (cont)
      (set! c cont)
      (cont 5))))
  10)
; => 25
(c 6)
; => 28
(+ 100 (c 6))
; => 28
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.
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.
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!
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

```scheme
(define cont 'uninitialized)
(if (call/cc (lambda (c)
  (set! cont c)
#t))
'something
'other-thing)
; => 'something
(cont #f)
; => 'other-thing
```
Storing continuations

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

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

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Storing continuations

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(define cont 'uninitialized)
(if (call/cc (lambda (c)
               (set! cont c)
               #t))
    'something
    'other-thing)
; => 'something
(cont #f)
```
Storing continuations

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

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

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

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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)))))
          prev
          (loop)))
    (loop)))
(fib-cont) ; => 1
(resume) ; => 1
(resume) ; => 2
(resume) ; => 3
(resume) ; => 5

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Continuations
Lecture 7A
(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
(define resume 'uninitialized)
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    (define (loop)
      (define next (+ prev cur))
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           (lambda (c)
             (set! resume (lambda () (c #f)))
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        prev
        (loop)))
    (loop)))
(fib-cont) ; => 1
(resume)  ; => 1
(resume)  ; => 2
(define resume 'uninitialized)
(define (fib-cont)
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         (cur 1))
    (define (loop)
      (define next (+ prev cur))
      (set! prev cur)
      (set! cur next)
      (if (call/cc
           (lambda (c)
             (set! resume (lambda () (c #f)))
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        prev
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    (loop)))
(fib-cont) ; => 1
(resume) ; => 1
(resume) ; => 2
(resume) ; => 3
(define resume 'uninitialized)
(define (fib-cont)
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    (define (loop)
      (define next (+ prev cur))
      (set! prev cur)
      (set! cur next)
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           (lambda (c)
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        prev
        (loop)))
    (loop)))
(fib-cont) ; => 1
(resume) ; => 1
(resume) ; => 2
(resume) ; => 3
(resume) ; => 5
Coroutines

- Save the continuation, return **true** now
- Save the continuation, return `true` now
- But call the continuation with `false` again, sometime in the future, to take the other branch
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- But call the continuation with `false` again, sometime in the future, to take the other branch
- In this case, resumes the loop!
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This pattern is known as a **coroutine**
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- Poor man’s threading (running multiple things at once)
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In this case, resumes the loop!
This pattern is known as a **coroutine**
Poor man’s threading (running multiple things at once)
...but we can do better...
Co-operative multithreading

- Only one bit of code can run at once, but we have multiple tasks to do

- "Co-operative" because tasks need to declare when they want to let someone else have a turn

Used by Mac OS 9, Windows 3.1

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