Advanced Scheme Techniques

Some Naughty Bits

Jeremy Brown

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And of course to SIPB, for organizing.

All errors are, of course, my fault alone.
Advanced Scheme

Day 2:
Continuations
Advanced Scheme Techniques

Scheme Requests for Implementation (SRFIs)

Several of the examples today will refer to SRFIs.

The SRFI documents represent the Scheme community’s de facto, post-R5RS standards

Check them out at http://srfi.schemers.org/
Anatomy of a Closure

In Scheme, procedures are *closures*.

A closure expects to be invoked with a certain number of arguments.

A closure contains:

- a pointer to some code
- a pointer to an environment
Closure Example

\[\texttt{((lambda (n)} \texttt{(lambda (x) (+ x n))) 5) ==> #<procedure object>}\]

The procedure object has pointers to::

- the code for adding x and n: (\texttt{(+ x n)}
- the environment binding n to 5
Procedure Call

When a function invokes a closure, it a single return value.

```
(define (pairify x y)
  (let ((val (cons x y)))
    val))
```

E.g., pairify expects cons to return a single value.
Return Information

A function must save information to return a value to its caller:

- a pointer to some code: the return address in the caller’s code
- a pointer to an environment: the caller’s execution environment
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- looks a lot like a closure (pointers to code and env)...
- that expects a single argument (the return value)...
Return Information

A function must save information to return a value to its caller:

- a pointer to some code: the return address in the caller’s code
- a pointer to an environment: the caller’s execution environment

This return-information:

- looks a lot like a closure (pointers to code and env)...
- that expects a single argument (the return value)...
- and never returns!
Continuations

Return-information represents the future path of a program.

Consider an actual closure which:

- expects a single argument, and
- never returns to its caller

Given this closure, we can view returning a value $V$ as calling $(k \ V)$. 
Continuations

A continuation is a closure which:

- represents the “future” of a computation from a given point
- never returns to its caller
- (usually) expects one argument — the value to be returned from the point at which the continuation was created
A Quick Review of Tail Calls

Consider

\[(\text{lambda} \ (x \ y) \ (y \ x))\]

The lambda will return the value returned by \((y \ x)\) — we call \((y \ x)\) a tail-call.
A Quick Review of Tail Calls

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Since the lambda has done all its work by the time the tail-call is called, its environment, etc., do not need to be preserved.
A Quick Review of Tail Calls

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Scheme implementations are required to support unbounded numbers of active tail calls.
Normal Factorial

Normal fact:

\[
\text{(define (fact } n) \newline
\text{\quad (if (= } n \text{ 1) \newline}
\text{\quad \quad 1 \newline}
\text{\quad \quad (* } n \text{ (fact } (- n 1)))\newline
\text{\quad )} \newline
\text{(fact 5) } \Rightarrow 120 \newline
\]
Normal Factorial

Normal fact:

(define (fact n)
  (if (= n 1)
      1
      (* n (fact (- n 1))))

(fact 5) ==> 120

What if we made all the implicit returns into explicit continuation calls? (Continuation-Passing Style)
Continuation Passing Style (CPS)

(define (cps-fact k n)
  (cps-=
    (lambda (eq-n-1)
      (if eq-n-1
        (k 1)
        (cps--
          (lambda (nval)
            (cps-fact
              (lambda (rval)
                (cps-* k n rval)) nval)) n 1))
      n 1)))

(cps-fact (lambda (x) x) 5) ==> 120

Note “inside-out” structure: every call is a tail call!
CPS call-with-current-continuation

call-with-current-continuation (AKA call/cc) makes the return continuation explicitly available as a closure.
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The CPS version of call/cc is simple:

(define (cps-call/cc k func)
  (func k k))

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```
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```

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The “normal” version of call/cc is a language primitive.

We need an example...
Early Return Using call/cc

Contrived example use of call/cc

(define evencount 0)

(let ((test 17))
  (call/cc (lambda (return)
    (if (odd? test) (return 5))
    (set! evencount (+ evencount 1))
    7)))
==> 5
**Early Return Using call/cc**

Contrived example use of call/cc

```
(define evencount 0)

(let ((test 17))
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    7)))
==> 5

(lambda (return...)) receives a continuation in return.
The continuation represents returning a value from the call/cc form.
When the continuation is invoked with the argument 5, the call/cc form immediately returns 5. The set! is never executed!
Continuations are First Class

Continuations...

- are first-class functions
- can be invoked many times
- can be used to create nearly any control-flow structure
Multiple-Value Continuations

Scheme limits normal functions to returning a single value.

In CPS-style, it’s easy to have multiple-value “return”:

```
(define (cps-values k . args)
  (cps-apply k args))
```

...all you need is a continuation (k, above) that accepts multiple values!
Multiple-Value Continuations

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  (cps-apply k args))
```

...all you need is a continuation (k, above) that accepts multiple values!

Scheme provides a language primitive “values” to return multiple values:

```
(lambda (a b)
  (values a b))
```

But how do we get the continuation that can accept them?
call-with-values

Scheme provides another primitive that works with values. From R5RS:

(call-with-values
  (lambda () (values 4 5)) ; producer
  (lambda (a b) (+ a b))) ; consumer
  ; (continuation)

==> 9

call-with-values calls the producer, providing the consumer as its continuation
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call-with-values calls the producer, providing the consumer as its continuation

SRFI-11 defines special forms LET-VALUES and LET*-VALUES which hide the call-by-values form
Control Flow Structures
Control Flow Structures

We’ve already seen early-return using continuations. Coming up:

- Exceptions
- Iterators/Co-routining
- Backtracking
- Multi-threading
Exceptions
Simple Exception Semantics

Simplest possible scheme:

```
(define (le10-or-bust x)
  (if (> x 10) (throw) x))

(let ((x 17))
  (try (lambda () 5)
       (le10-or-bust x)
       12))

==> 5
```
Simple Exception Semantics

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(let ((x 17))
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First argument to “try” is the handler; remainder args are body.
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Simple Exception Semantics

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  (if (> x 10) (throw) x))
```

```
(let ((x 17))
  (try (lambda () 5)
       (le10-or-bust x)
       12))

==> 5
```

First argument to “try” is the handler; remainder args are body. If (throw) is not called, the body’s return-value is try’s return-value. Handler is instantly invoked if (throw) is called while execution is in the try-form. Handler’s return-value is then also returned by the try expression.
Simple Exception Implementation

(define top-exception-handler (lambda () (error "unhandled")))
(define (throw) (top-exception-handler))
Simple Exception Implementation

(define top-exception-handler (lambda () (error "unhandled")))
(define (throw) (top-exception-handler))

(define-syntax try
  (syntax-rules ()
    ((try catch-clause body ...) (let* ((result #f)
        (old-handler top-exception-handler)
        (success (call/cc (lambda (cont)
            (set! top-exception-handler
                (lambda () (cont #f))))
            (set! result (begin body ...)) #t))
        (set! top-exception-handler old-handler)
        (if success result (catch-clause))))))
SRFI-34 Exceptions

SRFI-34 defines a more sophisticated exception-handling suite:

- Thrown exceptions include values
- Exception handlers can dispatch on values
- etc.

Check it out.
Backtracking
Backtracking: a Teaser

The “amb” operator always picks an acceptable value:

(let ((value (amb 0 1 2 3 4 5 6)))
  (assert (> value 2))
  (assert (even? value))
  value)

==>
Backtracking: a Teaser

The “amb” operator always picks an acceptable value:

(let ((value (amb 0 1 2 3 4 5 6)))
  (assert (> value 2))
  (assert (even? value))
  value)

==> 4
Backtracking: a Teaser

The “amb” operator always picks an acceptable value:

(let ((value (amb 0 1 2 3 4 5 6)))
   (assert (> value 2))
   (assert (even? value))
   value)

==> 4

And you can ask for more:

(next)

==> 6
Backtracking: An Application

(define (three-dice sumto)
  (let ((die1 (amb 1 2 3 4 5 6))
        (die2 (amb 1 2 3 4 5 6))
        (die3 (amb 1 2 3 4 5 6)))
    (assert (= sumto (+ die1 die2 die3)))
    (list die1 die2 die3)))

(initialize-amb-fail)

(three-dice 4)  ==>  (2 1 1)
(next)          ==>  (1 2 1)
(next)          ==>  (1 1 2)
(next)          ==>  ERROR:
                   amb tree exhausted
Amb: Principle of Operation

Amb works by backtracking

Think of amb as a glorified exception handler:

1. Pick a value and run forward
2. If no exception is thrown, great
3. If an exception is thrown, pick another value and run forward again
Amb: Framework

Everything but the definition of amb:

```
(define amb-fail '())

(define (initialize-amb-fail)
  (set! amb-fail
    (lambda (x)
      (error "amb tree exhausted"))))

(define (assert pred)
  (if (not pred) (amb)))

(define (fail) (amb))

(define (next) (amb))
```

Adapted from “Teach yourself Scheme in Fixnum Days (TYSiFD)", by Dorai Sitaram
**Amb: The Macro**

```
(define-syntax amb
  (syntax-rules ()
    ((amb argument ...)
      (let ((old-amb-fail amb-fail))
        (call/cc (lambda (return)
          (call/cc (lambda (next)
            (set! amb-fail next)
            (return argument)))) ...)
        (set! amb-fail old-amb-fail)
        (amb-fail #f))))))
```

Each ambiguous decision point adds to the stack.
Each failure backtracks to the last decision point.

Adapted from “Teach yourself Scheme in Fixnum Days (TYSiFD)”, by Dorai Sitaram
**Advanced Scheme Techniques**

**bag-of: Getting All the Options**

bag-of gives you a list of all acceptable solutions:

\[
(bag-of (three-dice 4))
\]

\[
=> ((1 1 2) (1 2 1) (2 1 1))
\]
**bag-of: Getting All the Options**

bag-of gives you a list of all acceptable solutions:

```
(bag-of (three-dice 4))
==> ((1 1 2) (1 2 1) (2 1 1))
```

And it’s recursive:

```
(bag-of
  (let ((sum (amb 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18)))
   (bag-of (three-dice sum))))

(let loop ((die 18))
  (if (>= die 3)
    (cons (bag-of (three-dice die)) (loop (- die 1)))
    '())))
```

==> (((6 6 6) (5 6 6) (6 5 6) (6 6 5)) ((4 6 6) (5 5 6) ....)
**bag-of: The Macro**

```scheme
(define-syntax bag-of
  (syntax-rules ()
    ((bag-of expr)
      (let* ((old-amb-fail amb-fail)
              (result '()))
        (if (call/cc (lambda (ifcondcont)
                       (set! amb-fail ifcondcont)
                       (let ((e expr))
                         (set! result (cons e result))
                         (ifcondcont #t)))
            (amb-fail #f))
          (set! amb-fail old-amb-fail)
          result))))
)```
Iterators
Traversals

It's easy to traverse a data structure recursively:

```
(define (list-traverse list)
    (if (pair? list)
        (list-traverse (cdr list)))
```
Traversals

It's easy to traverse a data structure recursively:

```scheme
(define (list-traverse list)
  (if (pair? list)
      (list-traverse (cdr list)))

(define (tree-traverse tree)
  (if (pair? tree)
      (begin
        (tree-traverse (car tree))
        (tree-traverse (cdr tree)))))
```
Traversals

It's easy to traverse a data structure recursively:

(define (list-traverse list)
  (if (pair? list)
      (list-traverse (cdr list)))))

(define (tree-traverse tree)
  (if (pair? tree)
      (begin
        (tree-traverse (car tree))
        (tree-traverse (cdr tree)))))

Not that these do anything useful
(define (list-iter list)
  (lambda ()
    (if list
        (let ((value (car list)))
          (set! list (cdr list))
          value)
        '())))

This is pretty clean, but...
A List Iterator

(define (list-iter list)
  (lambda ()
    (if list
      (let ((value (car list)))
        (set! list (cdr list))
        value)
      '()))

(define li (list-iter '(1 2 3))
(li) ==> 1
(li) ==> 2
(li) ==> 3
(li) ==> ()
A List Iterator

(define (list-iter list)
  (lambda ()
    (if list
      (let ((value (car list)))
        (set! list (cdr list))
        value)
      '()))
)

(define li (list-iter '(1 2 3))
(li) ==> 1
(li) ==> 2
(li) ==> 3
(li) ==> ()

This is pretty clean, but...
Iterating Over a Tree

(define (tree-iter tree)
  (let ((cell-stack (list tree)))
    (lambda ()
      (if cell-stack
        (let loop ((node (pop! cell-stack)))
          (if (pair? node)
              (begin
                (push! (cdr node) cell-stack)
                (loop (car node)))
              node))
        '())))

(define ti (tree-iter '(((1 . 2) . (3 . 4)))))
(ti) ==> 1  etc.

...now we’re keeping a history of the computation in cell-stack!
Tree Iterator Using Continuations and Macros

We add four lines to the tree-traverse routine:

```
(define (tree-iter tree)
  (with-caller caller loopstate ; save calling cont.
    (let loop ((node tree))
      (if (pair? node)
        (begin
          (loop (car node))
          (loop (cdr node)))
        (begin ; sequence
          (send caller loopstate node) ; send value
          '(()))))) ; 'done' value)
```

Adapted from “Teach yourself Scheme in Fixnum Days (TYSiFD)”, by Dorai Sitaram
Helper Macro: Send

(send caller localstate value)

Send gives the value to the ’caller’ continuation, storing the current continuation in the localstate variable:

(with-caller caller localstate body ...)

with-caller saves the calling continuation into caller, constructs the lexical execution environment in which localstate is bound, etc.
send

(define-syntax send
  (syntax-rules ()
    ((send to from value)
       (call/cc
        (lambda (state)
          (set! from (lambda () (state 0)))
          (to value))))))
**with-caller**

(define-syntax with-caller
  (syntax-rules ()
    ((with-caller caller iterator body ...) (let ((caller #f))
      (letrec ((iterator (letrec ((iterator
          (lambda ()
            (lambda ()
              (call/cc
                (lambda (caller-cont)
                  (set! caller caller-cont)
                  (iterator)))))))))))))
Tree Iterator Expansion I

(define (tree-iter-k list)
  (let ((caller #f)) ; caller continuation
    (letrec ((iterator
      (lambda ()
        (lambda ()
          (let loop ((list list))
            (if list
              (begin
                (call/cc
                  (lambda (iter)
                    (set! iterator (lambda () (iter 0)))
                    (caller (car list)))
                  (loop (cdr list)))
                (caller '()))))))))
... more
Tree Iterator Expansion II

... 

(lambda ()
  (call/cc
    (lambda (caller-cont)
      (set! caller caller-cont)
      (iterator)))))))
Cooperative Multi-Threading
Simple Goal

Three routines:

\begin{itemize}
\item (start-scheduling thunk)
\item (spawn thunk)
\item (yield)
\end{itemize}

- start-scheduling kicks off the threading system running thunk
- spawn may be called to create an additional thread from thunk
- yield may be called by one thread to let others run
Global State

(define thread-set '())

(define scheduler-context #f)
(define (start-scheduling thunk)
  (set! thread-set '())
  (call/cc
    (lambda (scheduler)
      (set! scheduler-context scheduler)
      (spawn thunk))
    (if (not (empty-stack? thread-set))
      (begin
        ((pop! thread-set))
        (loop)
        (display "**Scheduler exiting**"))))
Advanced Scheme Techniques

**spawn**

(define (spawn thunk)
  (push! (lambda () (thunk) (scheduler-context 0))
         thread-set))
yield

(define (yield)
  (call/cc
    (lambda (this-thread)
      (if (not (empty-stack? thread-set))
        (let ((next-thread (pop! thread-set)))
          (push! (lambda () (this-thread 0)) thread-set)
          (next-thread))))))
Example Code

(start-scheduling
   (lambda ()
      (spawn (lambda ()
                  (display "sub-thread")
                  (yield)
                  (display "more sub-thread")
                  (yield))
      (display "first thread")
      (yield)
      (display "and more first")))
Example Output

first thread
sub-thread
and more first
more sub-thread
Homework

Can you figure out how to implement locks in this system?
Other Continuation-Related Functions

Look these up sometime...

- dynamic-wind
- fluid-let
The End!